CONTRACT REPORT NO. 3-145

BEHAVIOR OF STABILIZED SOILS UNDER REPEATED LOADING

Report 2

BEHAVIOR IN REPEATED FLEXURE, FREQUENCY AND DURATION EFFECTS, FATIGUE FAILURE ANALYSES

by

J. K. Mitchell

C. L. Monismith

September 1966

Sponsored by

U. S. Army Materiel Command

Project No. 1-V-0-21701-A-046-05

Conducted for

U. S. Army Engineer Waterways Experiment Station

CORPS OF ENGINEERS

Vicksburg, Mississippi

Under

Contract No. DA-22-079-eng-414

by

Department of Civil Engineering

University of California

Berkeley, California

ARMY-MRC VICKSBURG, MISS.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

ABSTRACT

This report is the second in a series presenting the results of investigations of the behavior of stabilized soils under repeated loading. The studies have been organized within the framework of Corps of Engineers (1963) soil stabilization requirements for military roads and airfields in the theater of operations, and have the long range objectives of the development of improved criteria for quality design of stabilized soils and the establishment of suitable thickness design procedures.

This report presents the results of experimental investigations of the comparative behavior of cement-treated silty clay and cement-treated buckshot clay under repeated compressive stresses, the behavior of cement-treated silty clay in repeated flexure, and the effects of repeated load duration and frequency in both compression and flexure. Analyses are presented relative to the adequacy of stabilized layers to withstand flexural stresses imposed by the design trucks and aircraft specified by the Corps. Fatigue failure probabilities are examined and a method for assessing the probable effects on performance of variations in stabilized soil quality is described.

Test results have shown that different soil types, each stabilized to satisfy the same strength criteria (initial CBR of 4, stabilized soil CBR of 20 after a curing period of 24 hours) will not exhibit similar behavior under repeated loading. The nature of the variation of resilient modulus with stress intensity appears to be influenced significantly by cement treatment level.

Values of resilient modulus in flexure were found to be more than twice as great as those in compression for cement-treated silty clay. A fatigue curve was established for this material and showed that fatigue failure was probable for repeated flexural stresses greater than 60 percent of the initial strength. For samples not failing in fatigue, however, it was found that repeated flexural stresses caused a strength increase.

The effects of repeated loading frequency appear to be related primarily to the longer curing periods afforded to samples tested at low frequency. Resilient strains decrease to much smaller values at large numbers of load repetitions at low frequencies than at high frequencies.

The resilient modulus in flexure was found to vary with stress intensity at low frequencies. Previous findings that the resilient modulus in flexure was essentially independent of stress is not, therefore, of general applicability. Repeated load duration effects were not major.

Analysis of the stresses induced in pavements stabilized to satisfy Corps of Engineer's design criteria has shown that the flexural strength of the stabilized layer will be inadequate to prevent cracking. It does not follow, however, that performance would be inadequate for forward area military operations.

TABLE OF CONTENTS

FOREWARD

Studies of the Behavior of Stabilized Soils Under Repeated Loading were initiated at the University of California, Berkeley, in August 1964, under Contract No. DA-22-079-eng-414 for the U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi. This work is sponsored by the U. S. Army Materiel Command, DA Project No. 1-V-0-21701-A-046-05.

Contract Report No. 3-145 "Behavior of Stabilized Soils Under Repeated Loading, Report 1: Background, Equipment, Preliminary Investigations, Repeated Compression and Flexure Tests on Cement-Treated Silty Clay," December 1965, describes the studies for the period 17 August 1964 - 16 August 1965. The results of investigations made during the period 17 August 1965 - 16 August 1966 are presented and discussed in this report.

The investigations described herein were conducted under the supervision of Professors James K. Mitchell and Carl L. Monismith of the Department of Civil Engineering. The laboratory testing was done by Mr. Mian-Chang Wang and Mr. Stephen G. Wright, both graduate research assistants in Soil Mechanics.

List of Figures

I. INTRODUCTION

In 1964 investigations were initiated at the University of California, Berkeley, with long range objectives of developing improved criteria for quality design of stabilized soils and establishment of suitable thickness design procedures for these materials for use in military roads and airfields.

The Corps of Engineers (1963) established soil stabilization requirements for military roads and airfields in the theater of operations based on certain minimum initial soil strength conditions prior to treatment, maximum treatment levels, and minimum strengths at the end of a specified curing period. The CBR is used as the basic indicator of quality. Values of CBR and thickness of treated layer associated with specific wheel loads and numbers of coverages are specified for different classes of roads and airfields.

The Corps requirements have served as a guide in the selection of stabilization treatment and test conditions for these investigations. Of primary concern has been the behavior of stabilized soils under the action of short duration repeated loads simulating those applied by traffic to pavement structures. Information determined from repeated load tests is of value since it provides not only a check on the Corp's criteria (which are based on static tests), but also a basis for stress and deflection analyses of pavements, determination of fatigue properties and potential new procedures of pavement design.

Report 1 (Contract Report No. 3-145, December 1965) has presented background information for the study, description of tests for establishment of appropriate stabilization and test conditions, and results of repeated compression and flexure tests on cement-treated silty clay. Among the principal findings discussed in Report 1 are:

1. According to Corps of Engineers Criteria (1963) a minimum CBR prior to stabilization of 4 which will increase to 20 after treatment and 24-hours curing will meet all theater of operations requirements. To achieve this level of stabilization using portland cement, it was found that Vicksburg silty clay at an initial

water content of 18 to 19 percent (CBR = 4) required 3 percent cement and Vicksburg buckshot clay at an initial water content of 30 to 31 percent required 6 percent cement.

2. The modulus of resilient deformation (repeated stress intensity divided by resilient strain) in compression for treated silty clay decreased with increase in stress up to stress values of about 25 psi, but increased with increasing stress above this value. Values of resilient modulus ranged from 5,000 to 25,000 psi.
3. Strength increases and strain at failure decreases with increase in curing period. Cement-treated silty clay specimens of all ages were able to withstand at least 24,000 applications of a compressive stress equal to 80 percent of the strength at the start of loading.
4. Repeated applications of compressive stress at very early cur ng times may be beneficial in terms of ultimate performance.
5. A limited number of flexural test results suggested the existence of a fatigue relationship for cement-treated silty clay in terms of stress intensity and number of repetitions to failure.
6. Tensile strain at failure in beam specimens was only about one percent of the failure strain in compression.

In the period covered by the present report the investigations have been extended to the following areas of interest in the overall problem:

1. The behavior of cement-treated buckshot clay under repeated compressive stresses.
2. A detailed investigation of the behavior of cement-treated silty clay under repeated flexural stresses.
3. The effects of repeated load frequency on behavior of cement-treated silty clay.
4. The effects of repeated load duration on behavior of cement-treated silty clay.
5. Analysis of tensile stresses in stabilized pavements and their relationships to fatigue failure and cracking under the design loading conditions.

6. Analysis of the relationships between quality of stabilization in terms of cement content, curing time and initial water content and the wheel loads and pavement thicknesses at which treated silty clay will satisfy Corps of Engineers performance criteria without cracking developing in the pavement.

The results of these investigations are presented and discussed in this report. The significant findings are presented in graphical form in the main body of the report. Detailed test results are tabulated in the appendix.

II. BEHAVIOR OF CEMENT-TREATED BUCKSHOT CLAY IN REPEATED COMPRESSION

Introduction

The results of repeated load compression tests made on Vicksburg silty clay stabilized with 3 percent cement (adequate to satisfy Corps of Engineers' criteria for roads and airfields in terms of strength and CBR) were presented in Report 1. In order to investigate the generality of these results for other soil types stabilized to satisfy the same criteria, the behavior of cement-treated Vicksburg buckshot clay in repeated loading was also studied. Whereas the untreated silty clay is classified as (CL) and A-6 in the Unified and AASHO soil classification systems respectively, the buckshot clay is classified as (CH) and A-7 in the same systems. Classification, grain size and compaction data for these soils are shown in Appendix B.

For the buckshot clay a treatment level of 6 percent cement by weight at an initial soil water content of 30 percent was required to raise the CBR from 4 to 20 after 24 hours moist curing. These conditions resulted in a dry density of 90.2 lb per cu. ft. obtained by kneading compaction.

Treated Soil Properties

Fig. 1 shows the relationship between unconfined compressive strength and curing time for treated buckshot clay. The variation in strains at failure with curing time is shown in Fig. 2. While it is apparent that increased curing time leads to significant increases in strength, it should be noted that the increased brittleness as indicated by the decrease in failure strain may be detrimental from the standpoint of cracking under high loads.

The variation between unconfined compressive strength and curing time for Vicksburg silty clay treated with 3 percent cement is shown in Fig. 1 for comparison. These specimens were compacted at 19 percent water content and a dry density of 104 lb per cu. ft., as this combination also is adequate to raise an initial CBR of 4 to 20 after a curing period of 24 hours. It may be seen that while the strengths of the two soil types are not greatly

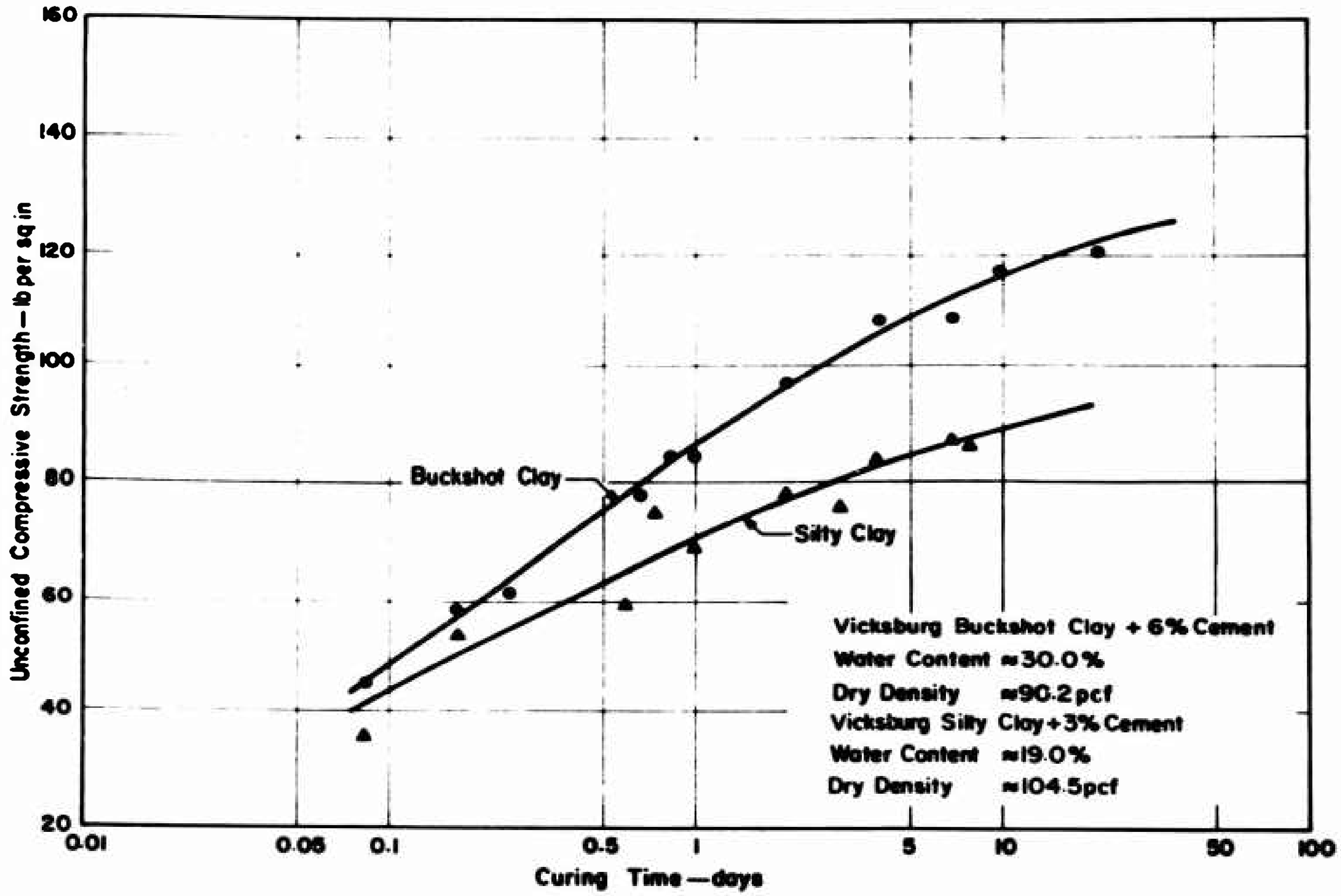


FIG.1 – COMPRESSIVE STRENGTH AS A FUNCTION OF CURING TIME FOR CEMENT-TREATED BUCKSHOT AND SILTY CLAY.

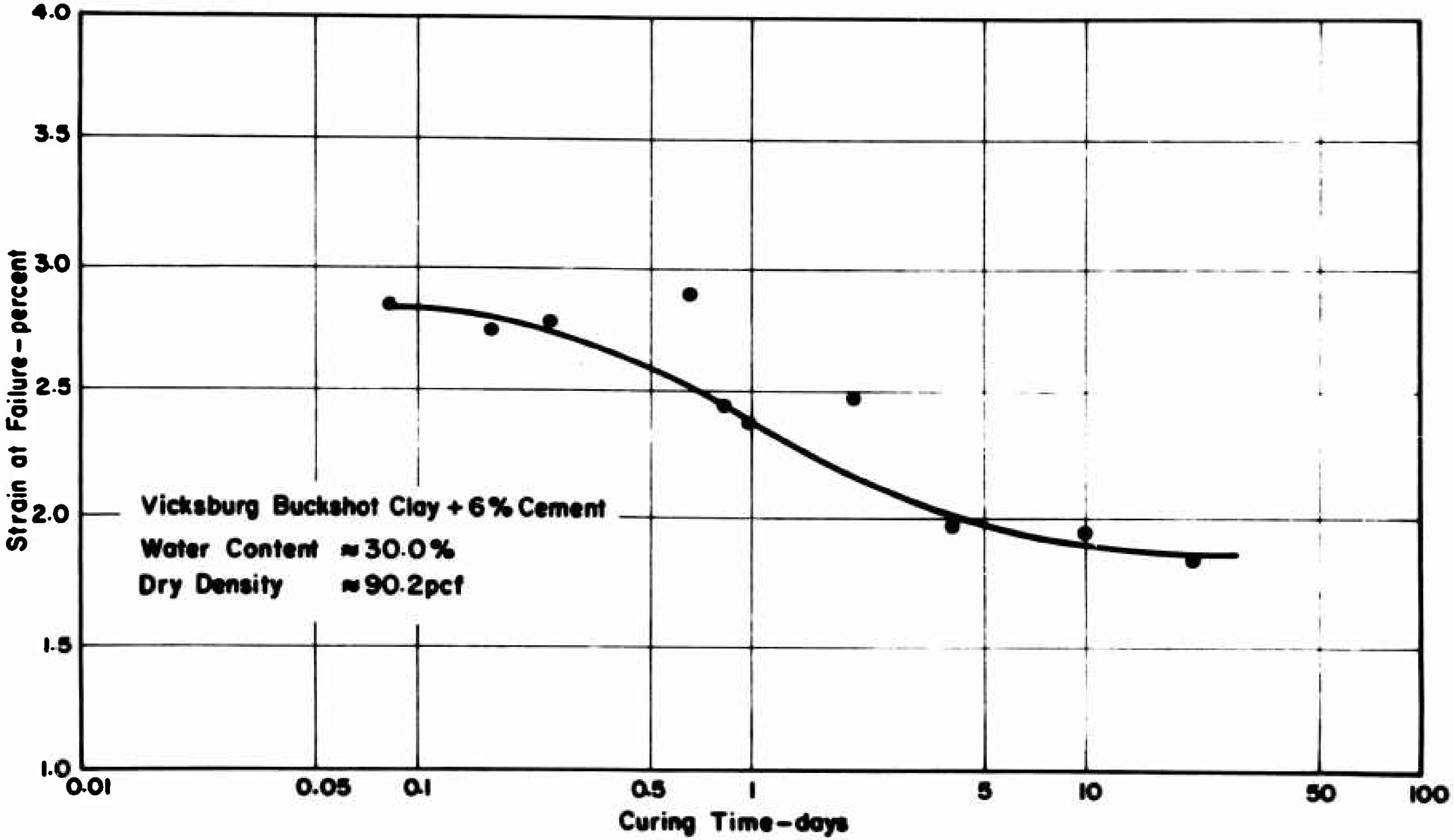


FIG.2 — COMPRESSIVE STRAIN AT FAILURE AS A FUNCTION OF CURING TIME FOR CEMENT-TREATED BUCKSHOT CLAY.

different at curing times of less than one day, the treated buckshot clay gains strength at a faster rate than the silty clay. This is perhaps to be expected because of the higher cement content used in the buckshot cla; Of more significance, however, is the fact that because two different soil are stabilized to achieve the same condition after a specified period, which in this case is a CBR of 20 after a curing period of 24 hours, it does not mean that the properties will be similar at other times. Furthei more, while the strains at failure for the buckshot clay were in the range of 2 to 3 percent, those of the silty clay were in the range of 5 to 8 percent.

Repeated Load Compression Tests

Repeated load compression tests were performed on specimens of treate buckshot clay cured for 24 hours using stress intensities from 11.6 to 93.0 percent of the strength as determined in normal compression tests. Apparatus and methods of testing are described in detail in Report 1. Fig. 3 shows the variation of total strain under the repeated stress as a function of number of load repetitions. Repeated loading was continued on each specimen until 24,000 repetitions had been recorded or failure occurred. It may be noted that the sample loaded to a stress intensity of 93 percent failed after 652 repetitions, and the sample subjected to a stress intensity of 87.2 percent failed after 4922 repetitions. Fig. 4 shows the relationships between resilient (recoverable) strain and number of repetitions for the same specimens. The form of the curves in Figs. 3 and 4 is generally similar to that observed for the treated silty clay (Figs. 25 and 26, Report 1).

The decreased resilience that develops with increasing numbers of load repetitions, Fig. 4, can be attributed to two causes:

(1) Slight densification and increase in stiffness resulting from the plastic deformations under low numbers of stress repetitions.

(2) Cement hydration which occurs during the testing period.

The variation of resilient modulus in compression with repeated stress intensity is indicated in Fig. 5. These results show a continuous decrease

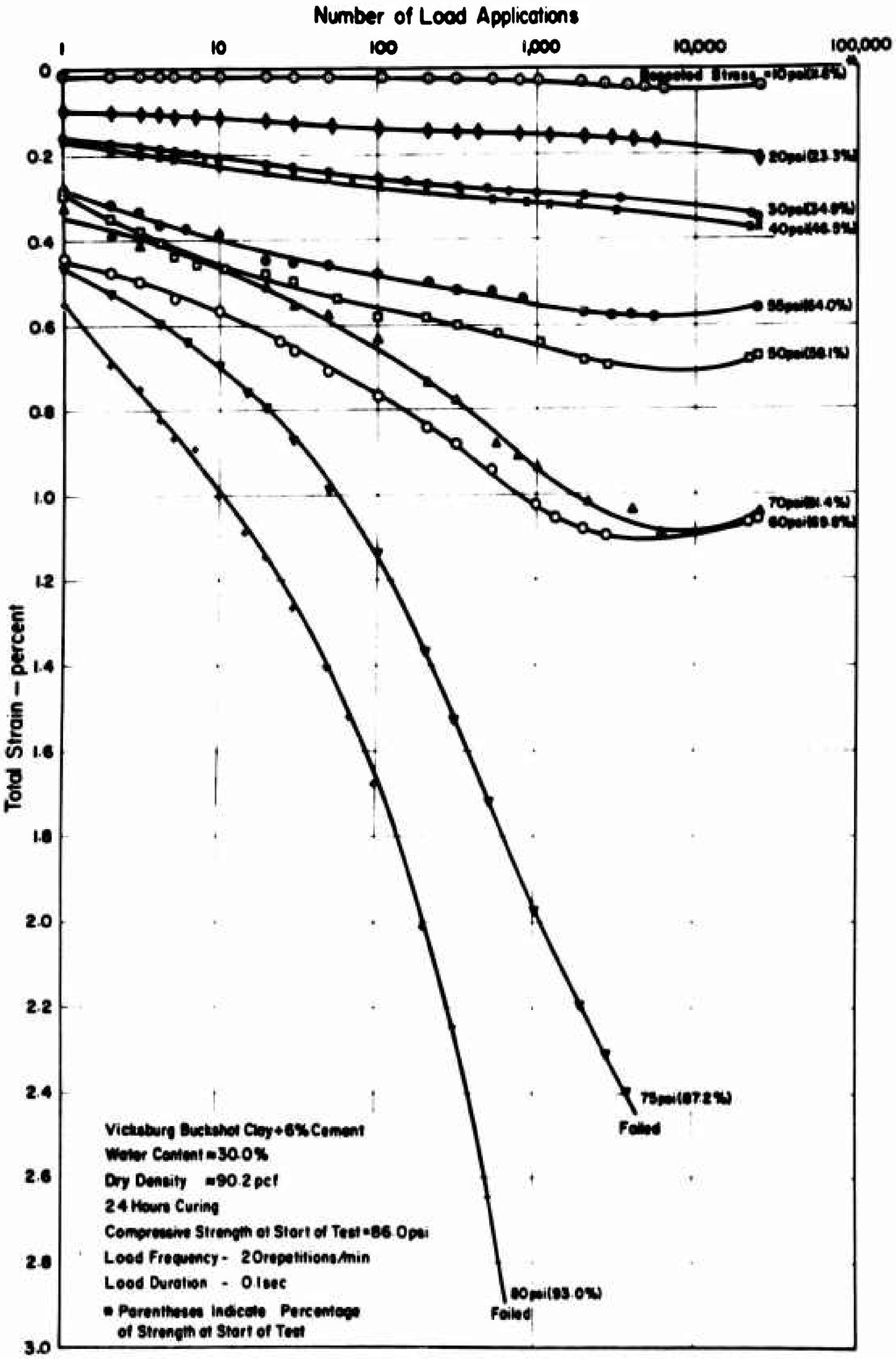


FIG.3 — TOTAL STRAIN AS A FUNCTION OF NUMBER OF COMPRESSIVE STRESS REPETITIONS FOR CEMENT-TREATED BUCKSHOT CLAY.

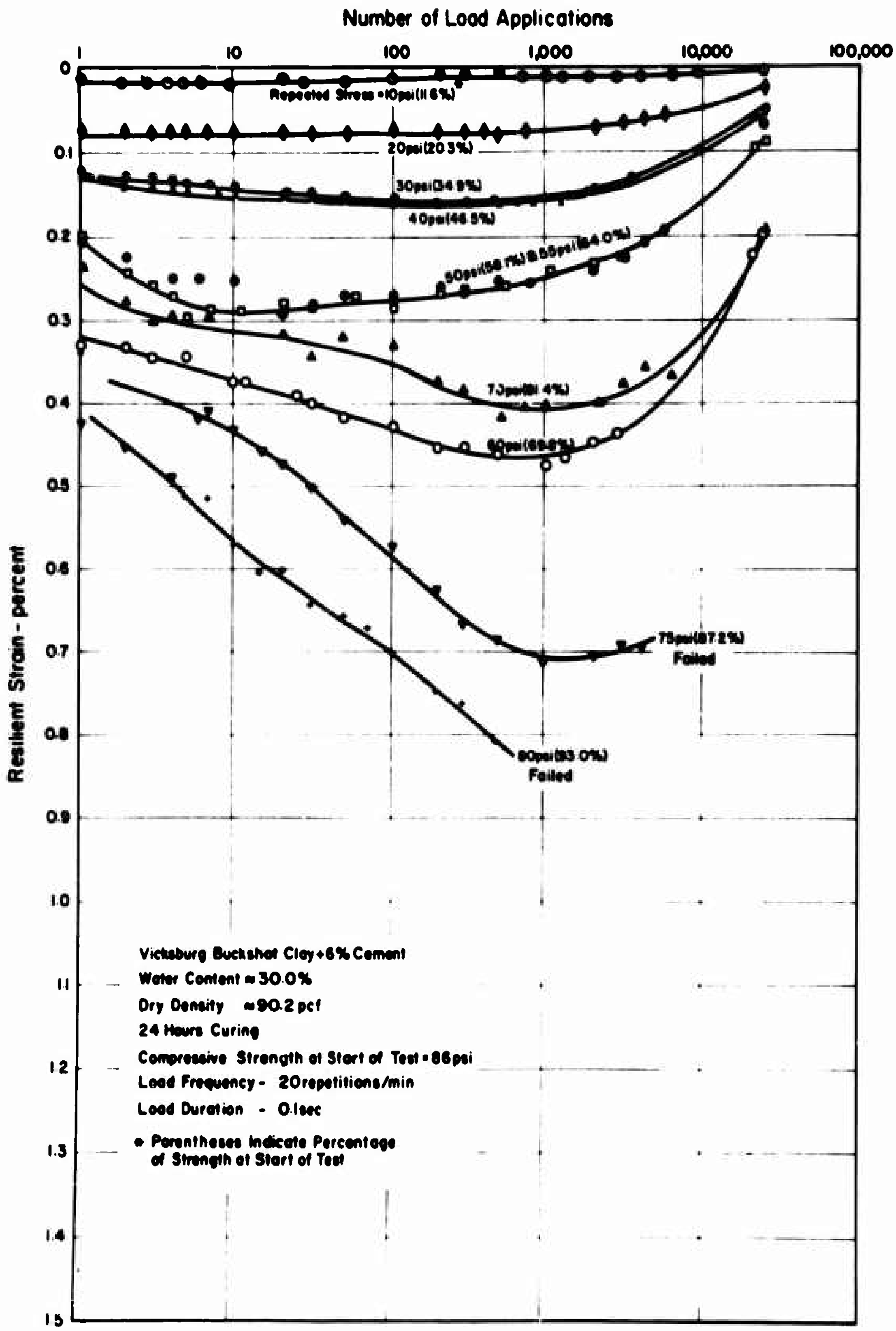


FIG.4 – RESILIENT STRAIN AS A FUNCTION OF NUMBER OF COMPRESSIVE STRESS REPETITIONS FOR CEMENT-TREATED BUCKSHOT CLAY.

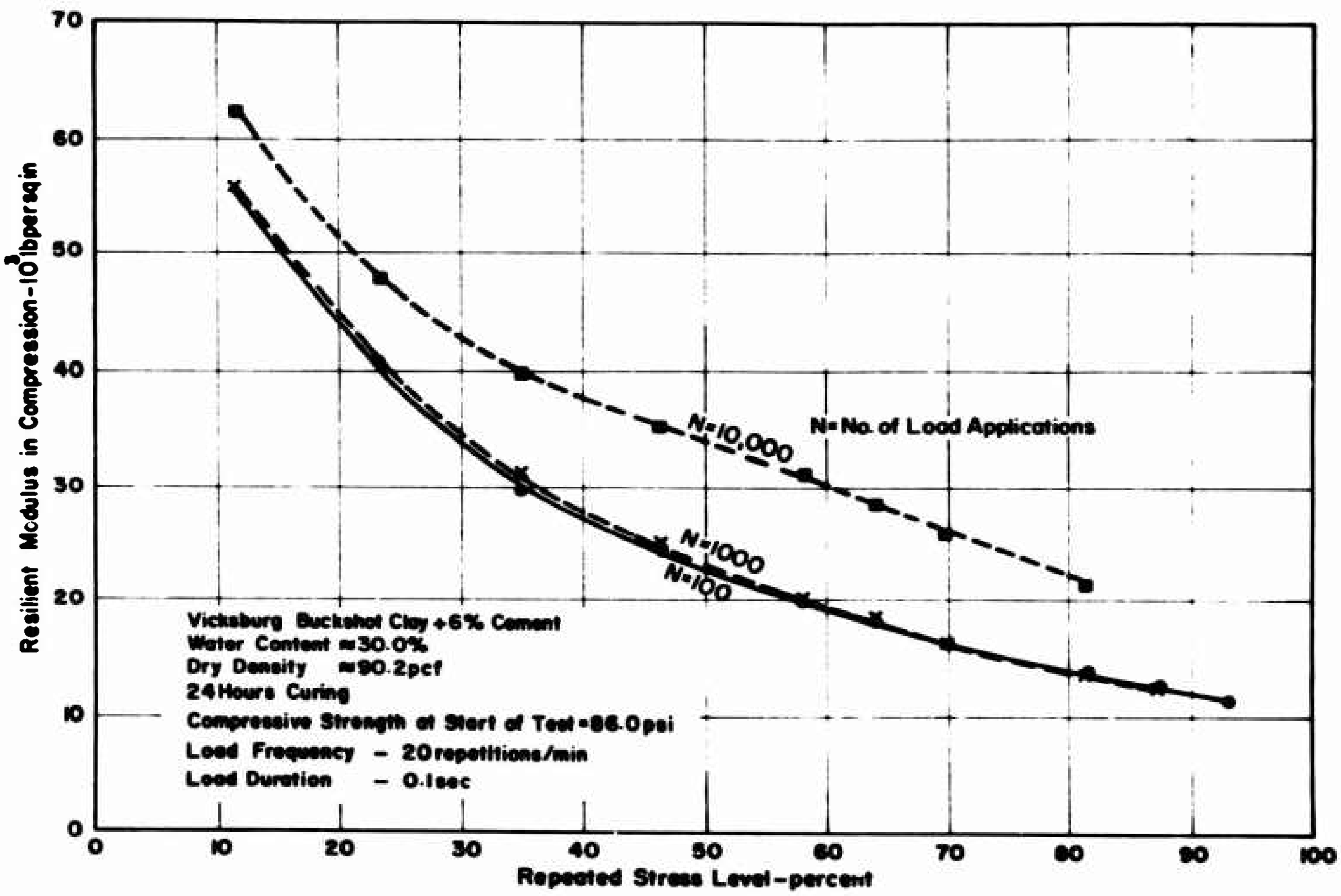


FIG.5– RESILIENT MODULUS AS A FUNCTION OF COMPRESSIVE STRESS INTENSITY FOR CEMENT-TREATED BUCKSHOT CLAY.

in modulus with increase in stress for the entire range of stresses investigated. While there is little difference between the modulus values after 100 and 1,000 stress repetitions, the modulus has increased significantly by 10,000 repetitions as a result of the decreased resilient strains.

Fig. 5 may be contrasted with Fig. 6 which shows similar results for tests on cement-treated silty clay. In the case of the silty clay the modulus decreased for stress increases up to about 20 psi, but then increased with further stress increase, probably as a result of densification under the higher stresses. This difference in behavior is probably attributable to the higher cement content used with the buckshot clay. Such a conclusion is supported by the fact that when silty clay is stabilized at high cement contents the relationship between modulus and stress intensity is similar to that for the cement-treated buckshot clay (Report 1, Figs. 30 and 31). It should also be noted that the values of resilient modulus are significantly greater for the treated buckshot clay than for the silty clay. These results provide further illustration that soil type is an important variable and that similar degrees of initial stabilization in terms of CBR or compressive strength do not necessarily lead to similar behavior under repeated loading.

The relationships between permanent strain, repeated stress intensity and number of load repetitions are shown in Fig. 7. Beyond a stress level of about 50 percent, the permanent deformation increases more than proportionally with stress intensity. It also continues to increase with number of load repetitions beyond 1000, in spite of the fact that resilient strains (Fig. 4) decrease significantly at large numbers of repetitions. Such accumulation of permanent deformation is related to the formation of ruts in actual pavement structures.

Effects of Repeated Load on Properties

Although specimens subjected to repeated compressive stress intensities of 87.2 and 93.0 percent of the 24-hour strength failed during repeated loading (Fig. 3), specimens subjected to smaller stress intensities satisfactorily withstood 24,000 stress repetitions. In fact, as may be seen from

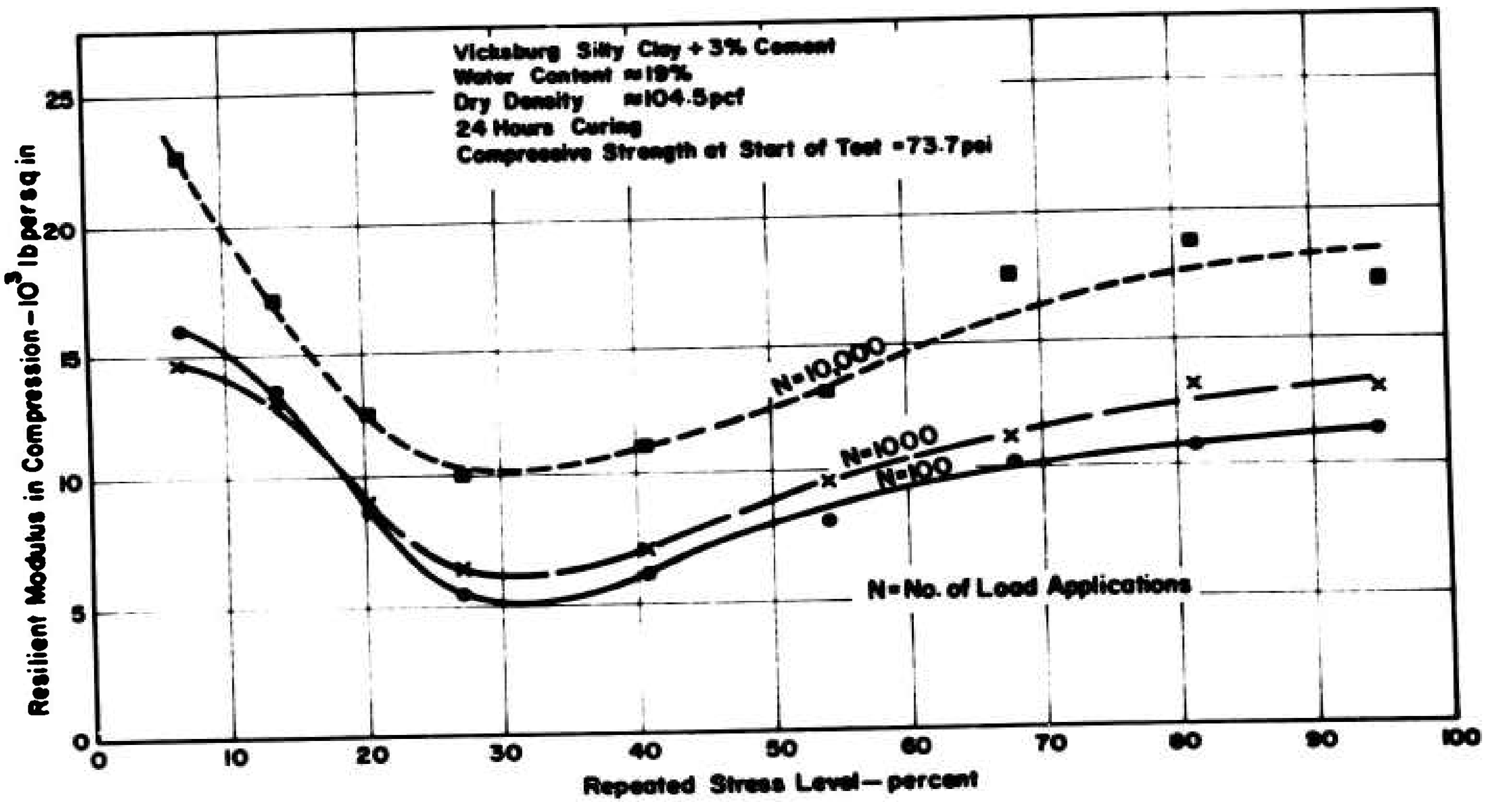


FIG.6— RESILIENT MODULUS AS A FUNCTION OF COMPRESSIVE STRESS INTENSITY FOR CEMENT-TREATED SILTY CLAY.(DATA FROM REPORT 1, 1965).

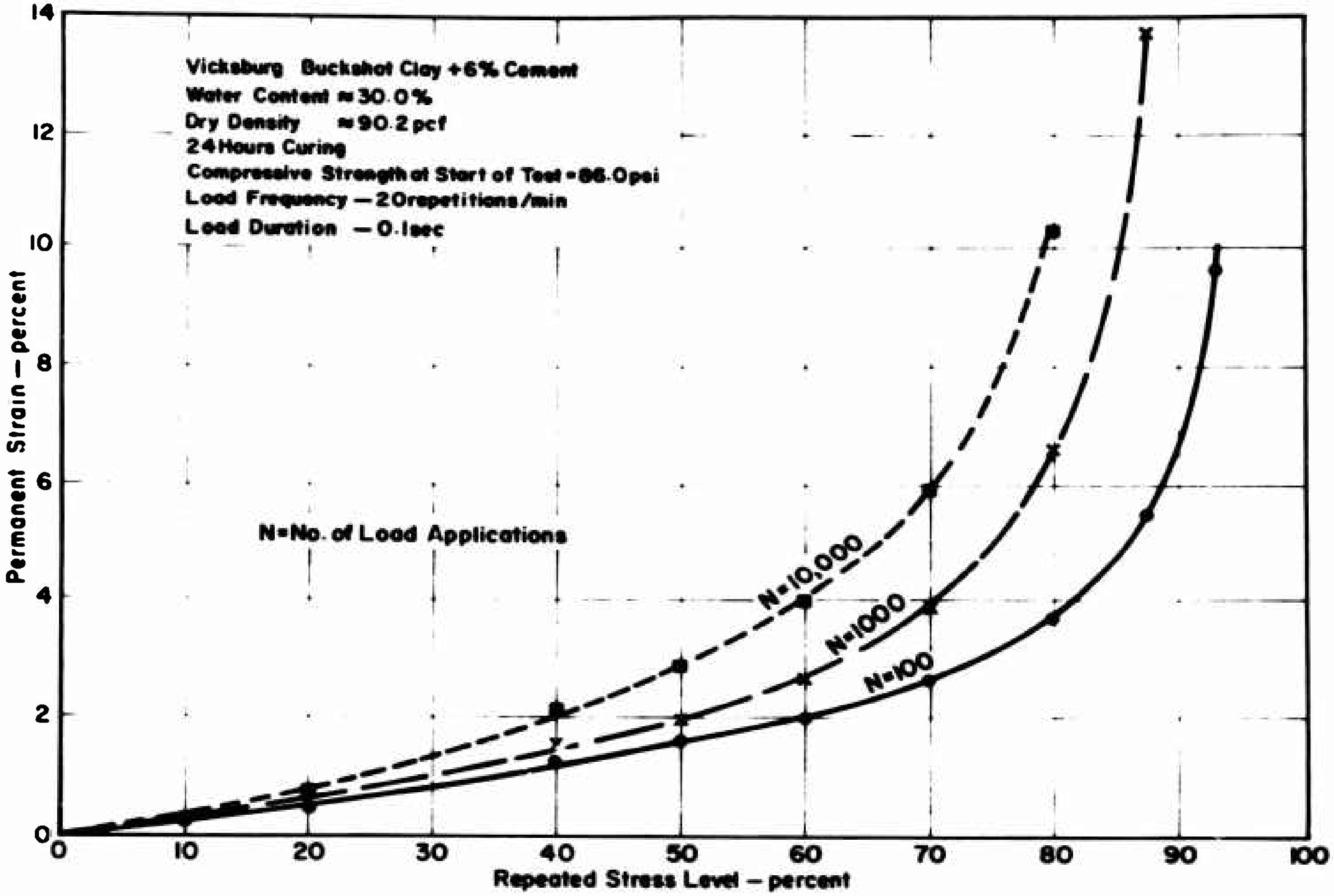


FIG. 7—PERMANENT DEFORMATION AS A FUNCTION OF REPEATED COMPRESSIVE STRESS INTENSITY FOR CEMENT-TREATED BUCKSHOT CLAY.

Fig. 8, these specimens were stronger at the end of repeated loading than identical samples of the same age but not subjected to repeated loading. Fig. 8 shows also that the additional strain to cause failure in static tests after repeated loading decreased with increased repeated stress intensities.

Thus it may be concluded that for those specimens not suffering fatigue failure, repeated stresses caused an increase in both strength and brittleness. From similar tests on cement-treated silty clay (Report 1) it was found that for stresses up to 75 percent of the initial strength repeated loading had no significant effect on the ultimate strength.

Summary

The results of the study of the behavior of cement-treated buckshot clay in repeated compression and the comparison of these results with those for similar tests on cement-treated silty clay permit the following conclusions and observations.

1. While static loading (CBR test) of the two treated soil types gave the same strength after a particular curing period, distinct differences in behavior were observed under repeated loading. Differences were also found under static loads for different curing periods.
2. The form of variation of resilient modulus with stress level appears sensitive to cement treatment level. For low treatment levels modulus values pass through a minimum with increasing stress level (Fig. 6) and for high treatment levels the modulus decreases with increasing stress for the entire range of stresses investigated.
3. Although both the treated silty clay and treated buckshot clay had the same CBR at the start of repeated loading, resilient moduli for the buckshot clay specimens were considerably greater than for the silty clay specimens, particularly at the lower stress levels.
4. Soil type and treatment level may affect significantly the influence of repeated loading on strength and brittleness.

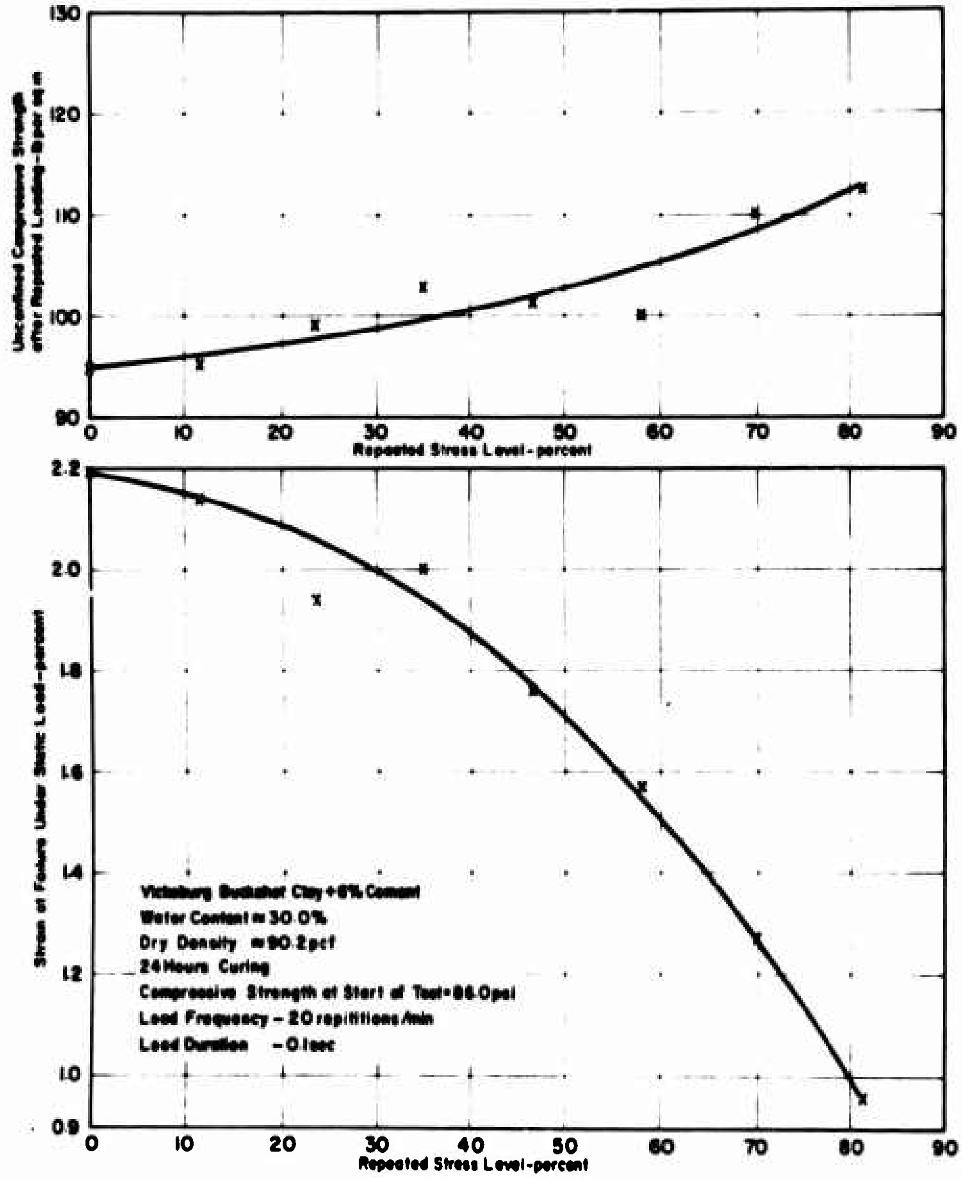


FIG.8 – EFFECT OF REPEATED COMPRESSIVE STRESS ON PROPERTIES OF CEMENT-TREATED BUCKSHOT CLAY.

III. BEHAVIOR OF CEMENT-TREATED SILTY CLAY IN REPEATED FLEXURE

Introduction

Limited data were presented in Report 1 concerning the response of Vicksburg silty clay treated with 3 percent cement to repeated flexural stresses. A more extensive study of the flexural properties of this material has been completed which includes the influences of stress intensity, water content, and curing period. In addition the fatigue characteristics of beam specimens have been investigated.

Beam specimens 12-in. long by 3-in. wide by 2-in. high were prepared using kneading compaction. After curing, the samples were tested as simple beams with a concentrated load at the center using the apparatus described in Report 1. Computation of tensile stresses in flexure were made using the known loading conditions and measured deflections at the center of the beam in conjunction with simple beam theory. It is possible that the values determined in this way are somewhat in error because of non-linear stress vs strain behavior and non-linear stress variations across the beam section. Any errors from these sources are probably not serious and should have no significant effect either on the trends observed or the comparisons made.

Because of the simple support conditions used for the beam specimens, all specimens were subjected to a dead load stress. For the size and density of the samples used, this stress amounted to 3.1 psi compression and tension at the top and bottom of the beam, respectively and corresponds to about 15 percent of the strength of the beam which has been treated to give a CBR of 20 after 24 hours curing. Tensile strain at the bottom of the beam from the dead load was estimated to be approximately 1.5×10^{-2} percent. In the following discussion the dead load stress and strain are included in all strength and total strain values. The reported values of repeated load and repeated stress level represent stresses applied to the beam in excess of the dead load stress which acts continuously.

While more sophisticated beam testing apparatus can be assembled to eliminate dead load effects, the simplicity of the present apparatus and

test procedure coupled with the relatively minor effects of dead load made it more suitable.

Flexural Properties of Treated Soil

The variations of dry density, flexural strength (maximum tensile stress at the bottom of the beam), and tensile strain at failure with water content are shown in Fig. 9. Since compaction of all mixtures was at water contents wet of optimum, an increase in water content resulted in a decrease in density. In Fig. 9 it may be noted that strength decreases with increase in water content. At the same time the strain at failure increases, thus indicating decreased brittleness with increased water content. As would be expected increased curing time results in higher strengths but lower strains at failure.

The variations of flexural strength and strain at failure with curing time for specimens of cement-treated silty clay are shown in Fig. 10. The samples used for this test series were prepared at a water content of 19 percent and a dry density of 105.8 pcf. The variations are consistent with progressive hydration of the cement as curing proceeds.

Effect of Stress Intensity on Behavior in Repeated Flexure

Beam specimens of silty clay stabilized with 3 percent cement and compacted at a water content of 19 percent were subjected to repeated flexural stresses in the range of 12.5 to 100 percent of the flexural strength in normal flexure tests after a 24 hour curing period. All repeated load tests were conducted at a frequency of 20 repetitions per minute and a load duration of 0.1 sec. All samples were subjected to 24,000 load repetitions over a 20 hour period unless failure occurred at a lesser number.

Fig. 11 shows the variation of total strain with stress intensity after different numbers of load repetitions. It may be noted that, in the absence of fatigue failure, the increase in total deformation subsequent to 1000 load repetitions was not great. Similar data for resilient strains are shown in Fig. 12. These data show that resilient

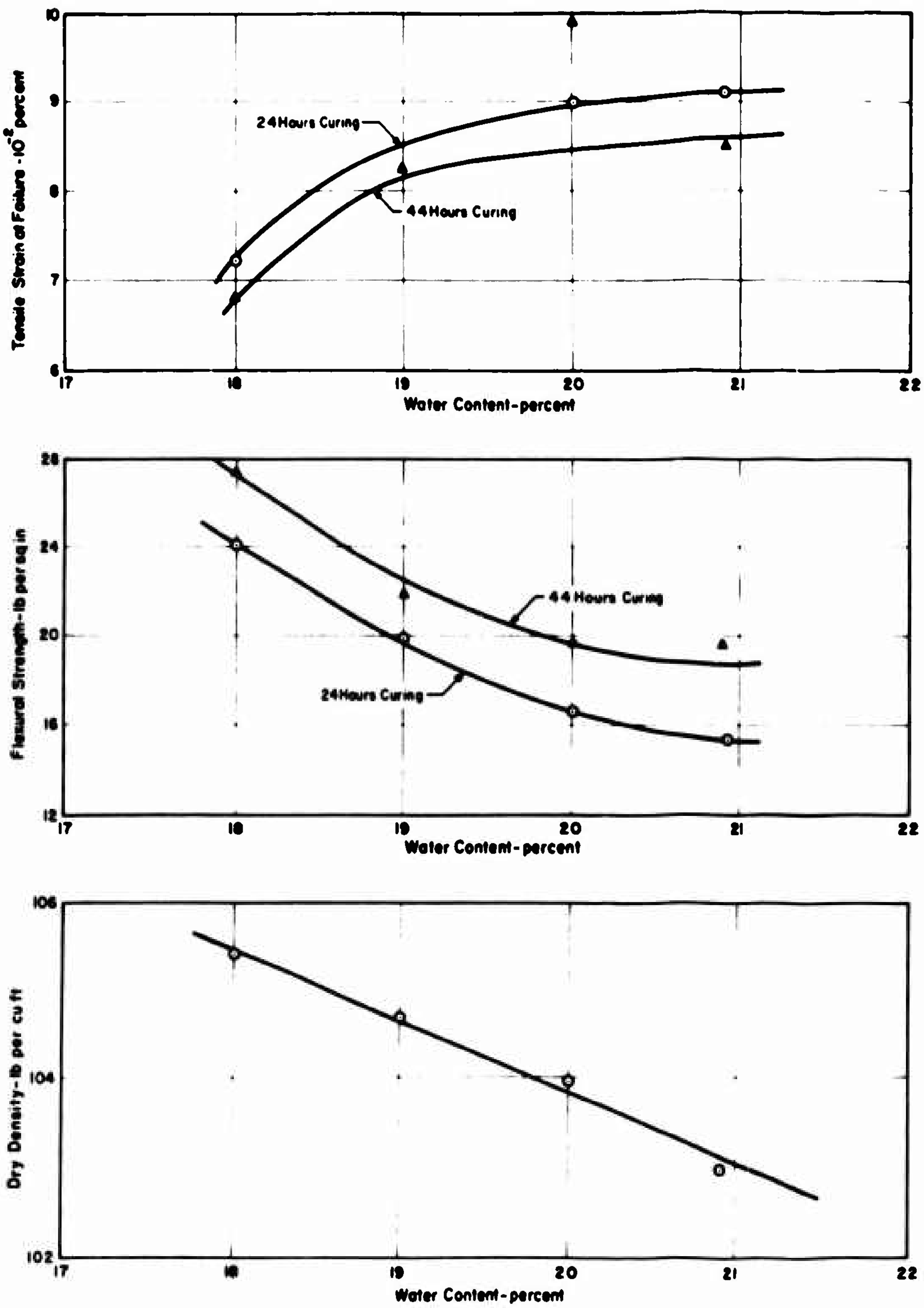


FIG.9— PROPERTIES OF CEMENT-TREATED SILTY CLAY BEAM SPECIMENS.

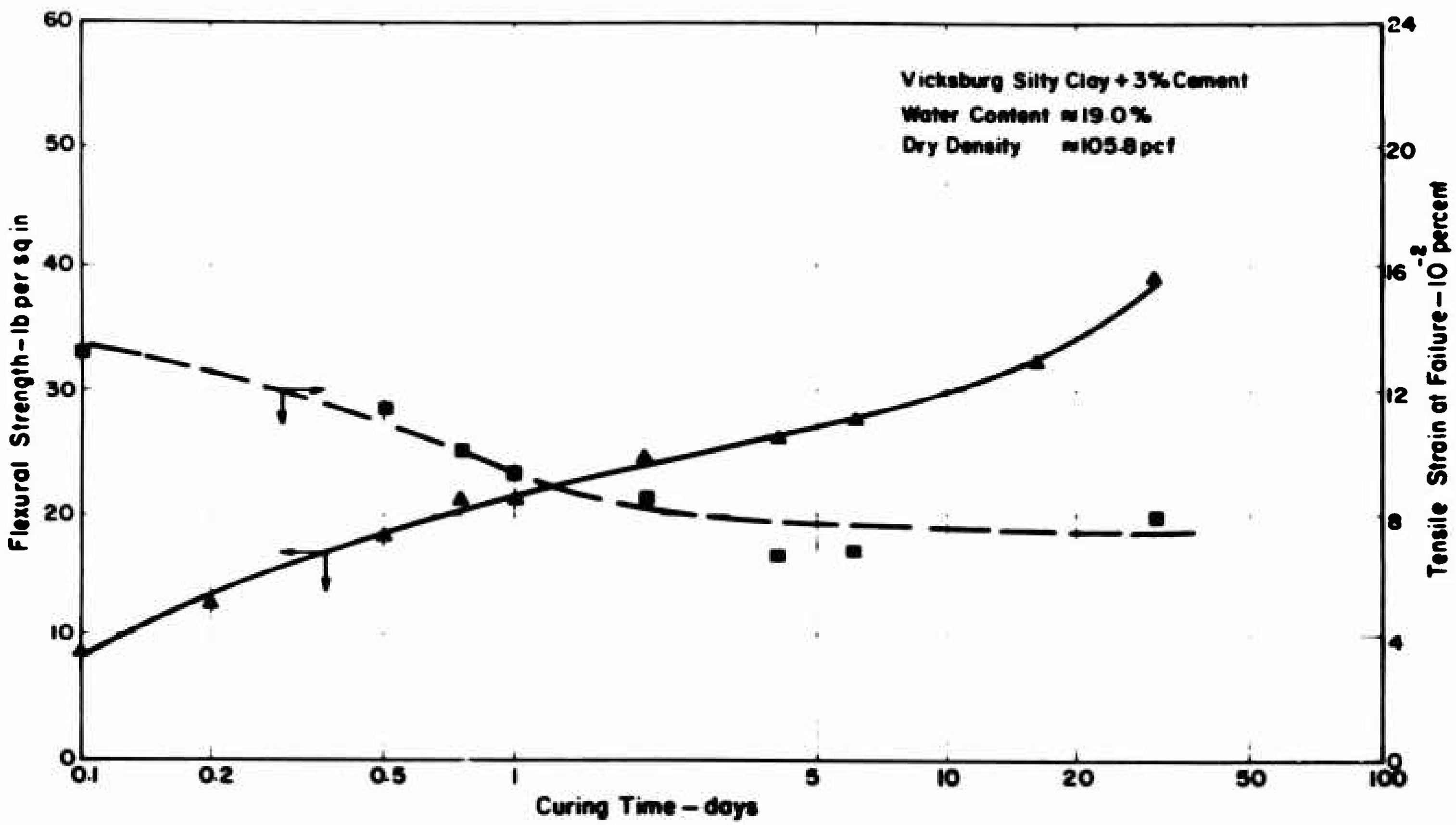


FIG.10- EFFECT OF CURING TIME ON FLEXURAL STRENGTH AND STRAIN AT FAILURE FOR CEMENT-TREATED SILTY CLAY.

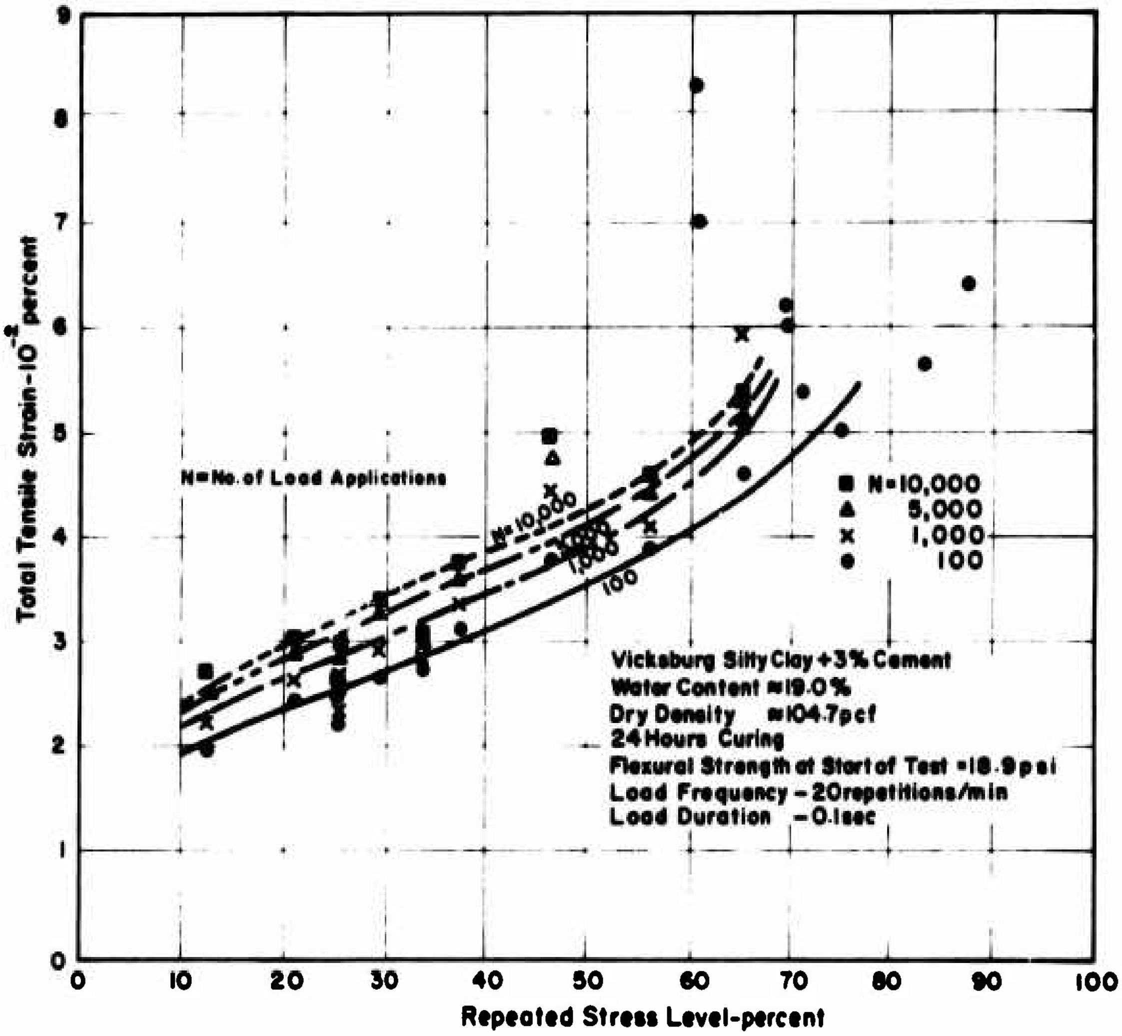


FIG.11– VARIATION OF TOTAL STRAIN WITH REPEATED FLEXURAL STRESS INTENSITY FOR CEMENT-TREATED SILTY CLAY.

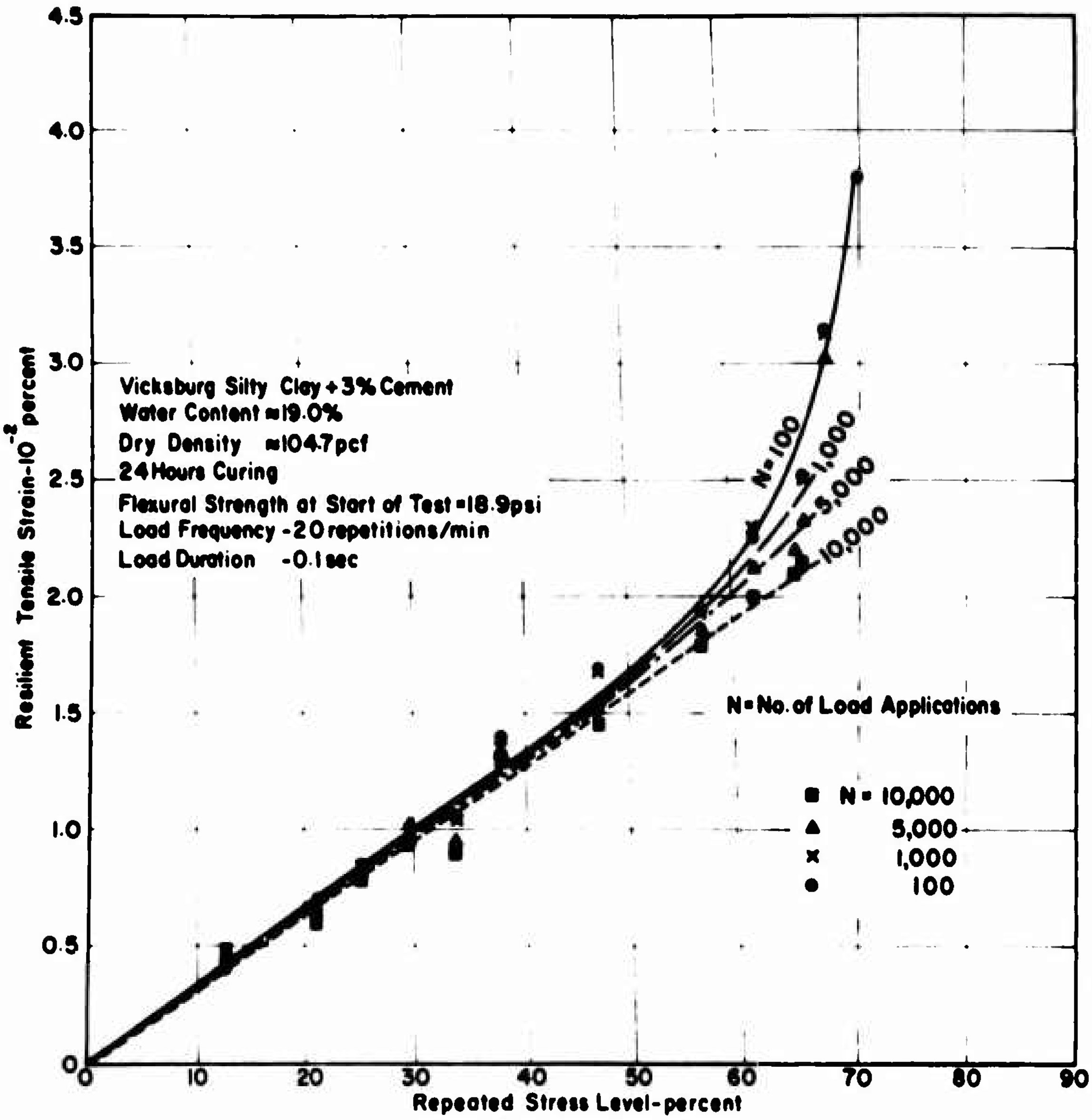


FIG. 12 – VARIATION OF RESILIENT STRAIN WITH REPEATED FLEXURAL STRESS INTENSITY FOR CEMENT-TREATED SILTY CLAY.

strain is relatively insensitive to number of repetitions except at high stress levels where fatigue failure developed. Comparison of Figs. 10 and 11 shows that the resilient strain amounted to approximately half of the total strain at any stress intensity.

The linearity between resilient strain and repeated flexural stress at stress intensities less than about 50 percent of the strength indicates that modulus of resilient deformation in flexure is independent of stress intensity. This point is illustrated in Fig. 13 which shows modulus of resilient deformation as a function of stress level for different numbers of load repetitions. These curves can be compared with those for the resilient modulus in compression, Fig. 6. Just why the resilient modulus in flexure should be virtually independent of stress intensity; whereas the modulus in compression varies significantly, is not altogether clear. However, similar behavior has been observed for the silty clay treated with 13 percent cement to form soil-cement (Shen and Mitchell, 1966). It is of interest also that the magnitude of the flexural modulus is more than twice that in compression.

As is true for most structural materials a large number of high magnitude repeated flexural stresses resulted in fatigue failures of the treated silty clay by cracking. The higher the stress the fewer the repetitions required to cause failure. Fig. 14 shows the relationship between the number of repetitions to cause failure and repeated flexural stress intensity. The data show some scatter; however, this is to be expected since the specific number of repetitions at which cracking becomes sufficient to cause complete failure is very sensitive to small defects in structure, local stress concentrations, etc. The observed behavior is indication of the stochastic nature of fatigue and is consistent with that observed in other paving materials such as asphalt concrete as discussed by Deacon and Monismith (1966).

The fatigue curve in Fig. 14 indicates that the cement-treated silty clay can probably withstand repeated stress intensities of 60 percent or less of the flexural strength without suffering fatigue failure. Little additional fatigue data for cement-stabilized soil are available.

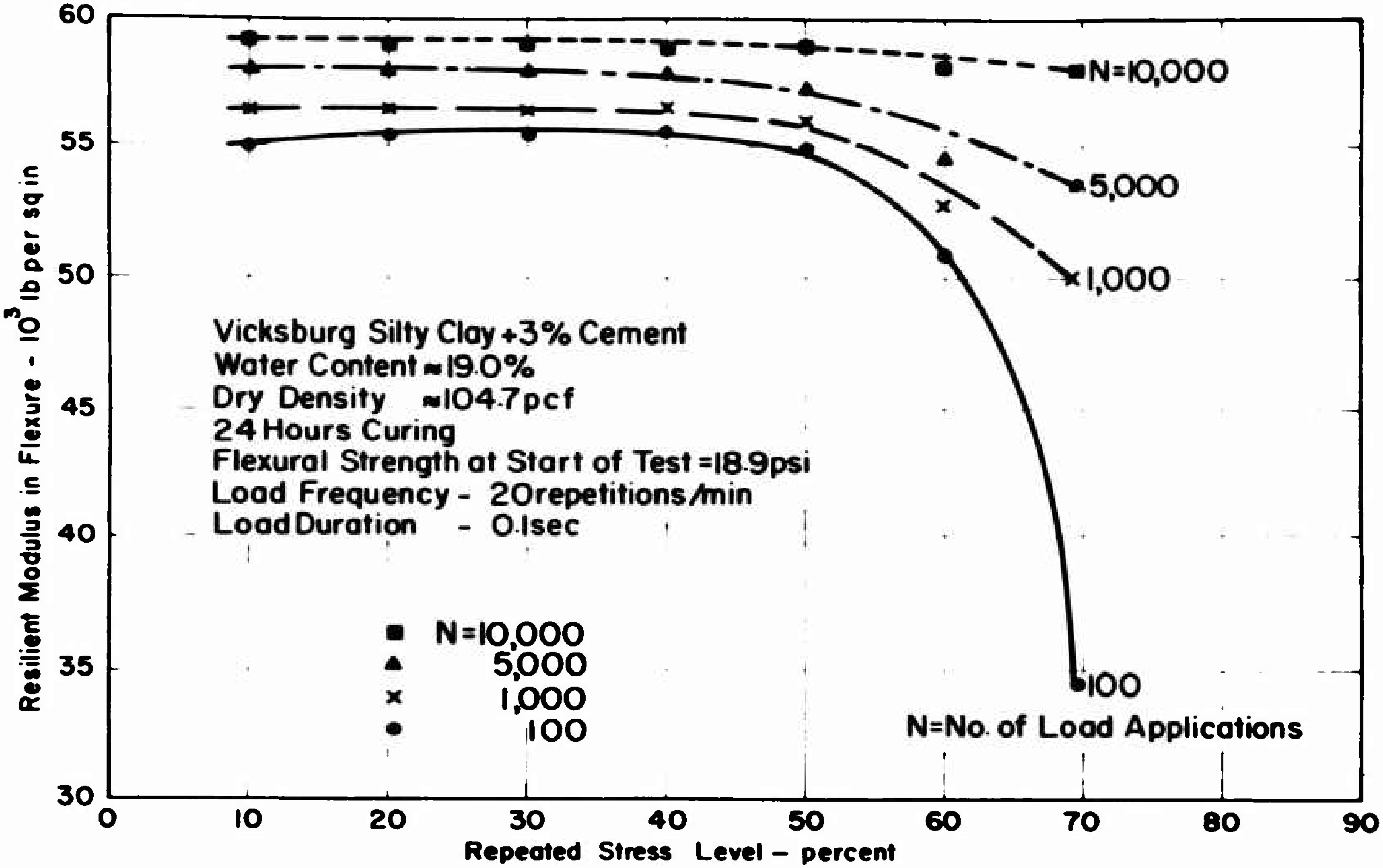


FIG.13– INFLUENCE OF FLEXURAL STRESS INTENSITY ON RESILIENT MODULUS FOR CEMENT-TREATED SILTY CLAY.

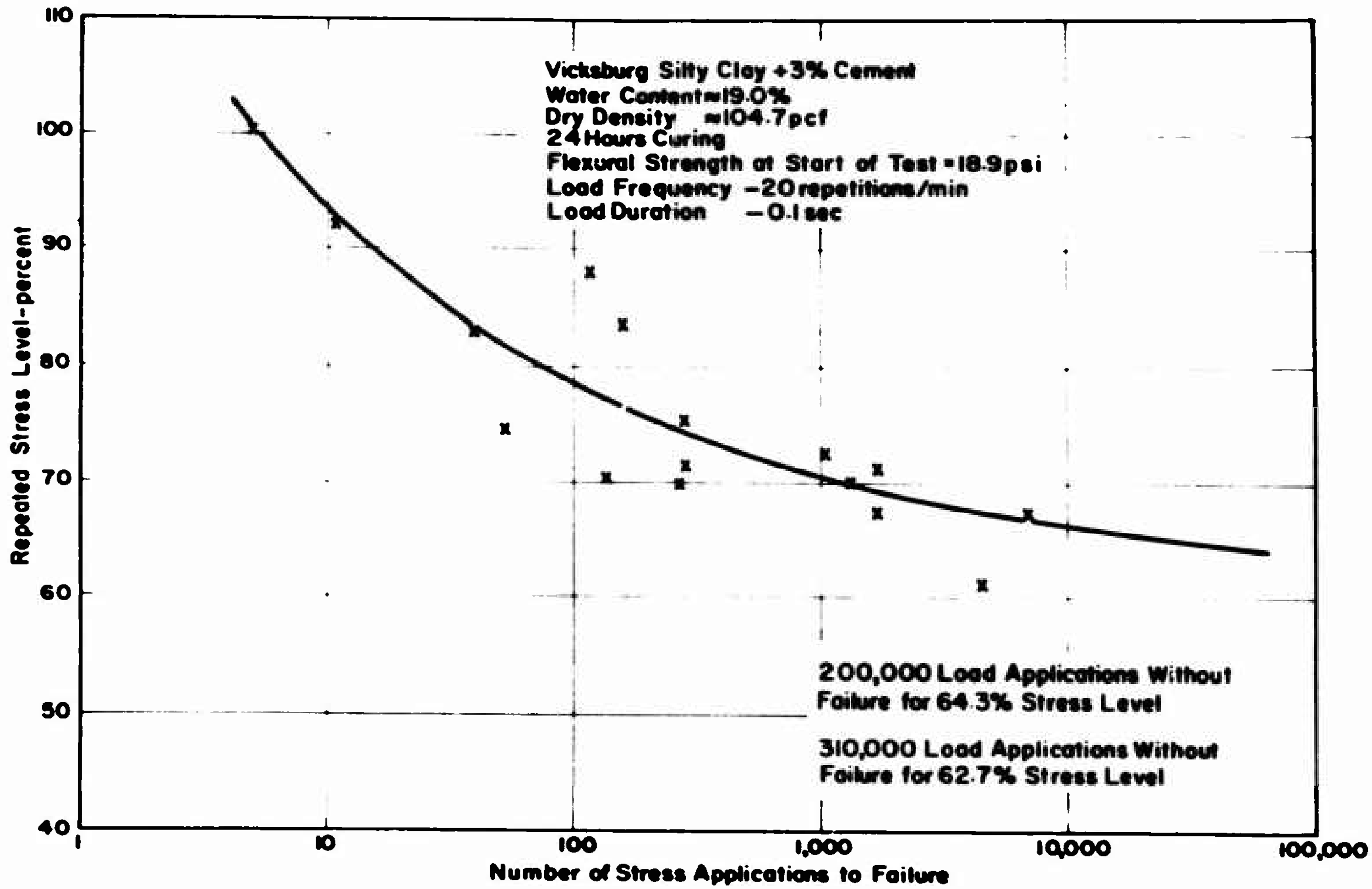


FIG. 14— FLEXURAL FATIGUE CURVE FOR CEMENT-TREATED SILTY CLAY.

Bofinger (1965) studied the fatigue behavior of a heavy black clay at cement contents of 8, 12 and 16 percent in repeated compression, tension, and flexure. He observed no fatigue failures in compression. On the other hand fatigue in flexure and direct tension developed at stresses as low as 40 percent of the strength. It was found also that the "fatigue limit," i.e., the actual stress below which an unlimited number of stress repetitions would not cause failure, was independent of cement content. On the basis of this finding Bofinger concluded that it is pointless to include excess cement in soil-cement pavements. It is probably premature to proceed on this basis, however, until additional data are available for other soils, treatment levels, and curing conditions.

The fatigue relationship shown in Fig. 14 is germaine to the military road and airfield stabilization problem in that Corps criteria specify certain loadings, numbers of coverages, pavement thicknesses and subgrade and pavement strengths. Further analysis of fatigue as related to the military road and airfield problem is presented in Chapter VI of this report.

Effect of Water Content on Behavior in Repeated Flexure

Repeated load flexural tests were made on beams of silty clay treated with 3 percent cement and compacted at average water contents of 18, 19, 20, and 20.8 percent. All specimens were cured for 24 hours prior to testing. A repeated load frequency of 20 repetitions per minute and a duration of 0.1 sec were used. Strengths, strains at failure, and densities of these specimens at the start of repeated loading are indicated in Fig. 9. Repeated stress intensities of 45 to 80 percent of the initial strength were used. Tests were continued to 24,000 repetitions unless failure first occurred.

In general the behavior at each water content was similar to that for the tests described in the previous section for a water content of 19 percent. Thus only a comparison between behavior at different water contents will be presented here. More complete test results are tabulated in the Appendix.

Fig. 15 shows the variation of resilient and total strain with repeated flexural stress for beams at different water contents. The values shown are those obtained after 100 load repetitions. Similar behavior is exhibited at other numbers of load repetitions, except for those cases where fatigue failure was imminent. As would be anticipated an increase in water content leads to increases in both resilient and total strain. In the range of the highest water contents studied, 20 and 20.8 percent, water content appeared, however, to have little effect on strains. Fig. 9 indicates that static strength and failure strain are little affected by water content variations in this range as well. These trends are shown more clearly in Fig. 16 where the resilient and total strain as a function of water content for 100, 1000, and 10,000 load repetitions are plotted for repeated flexural stresses of 5 and 8 psi.

Resilient moduli in flexure corresponding to stress intensities of 5 and 8 psi are shown in Fig. 17 as a function of water content. It may be seen that rather substantial variations in modulus may occur for water contents in the range of 18 to 20 percent. Since water content variations in this range are inevitable for any field condition it would be unrealistic to expect that a single precise value of modulus will hold throughout the construction.

Insufficient data have been obtained to define complete fatigue curves at each water content investigated. Some indication of the fatigue characteristics is available, however, and is shown in Fig. 18 in terms of the approximate stress (indicated as a range) required to cause failure within 24,000 load repetitions. It may be seen that this stress is sensitive to water content and decreases as water content increases. This would be expected since strength also decreases with water content. Fig. 19 shows the same information in terms of stress level, i.e., each stress expressed as a percentage of the strength at the particular water content. Even on this basis water content appears to influence the fatigue behavior. Thus it would seem that the cement-treated silty clay should be considered, in terms of fatigue response, as a somewhat different material at each water content.

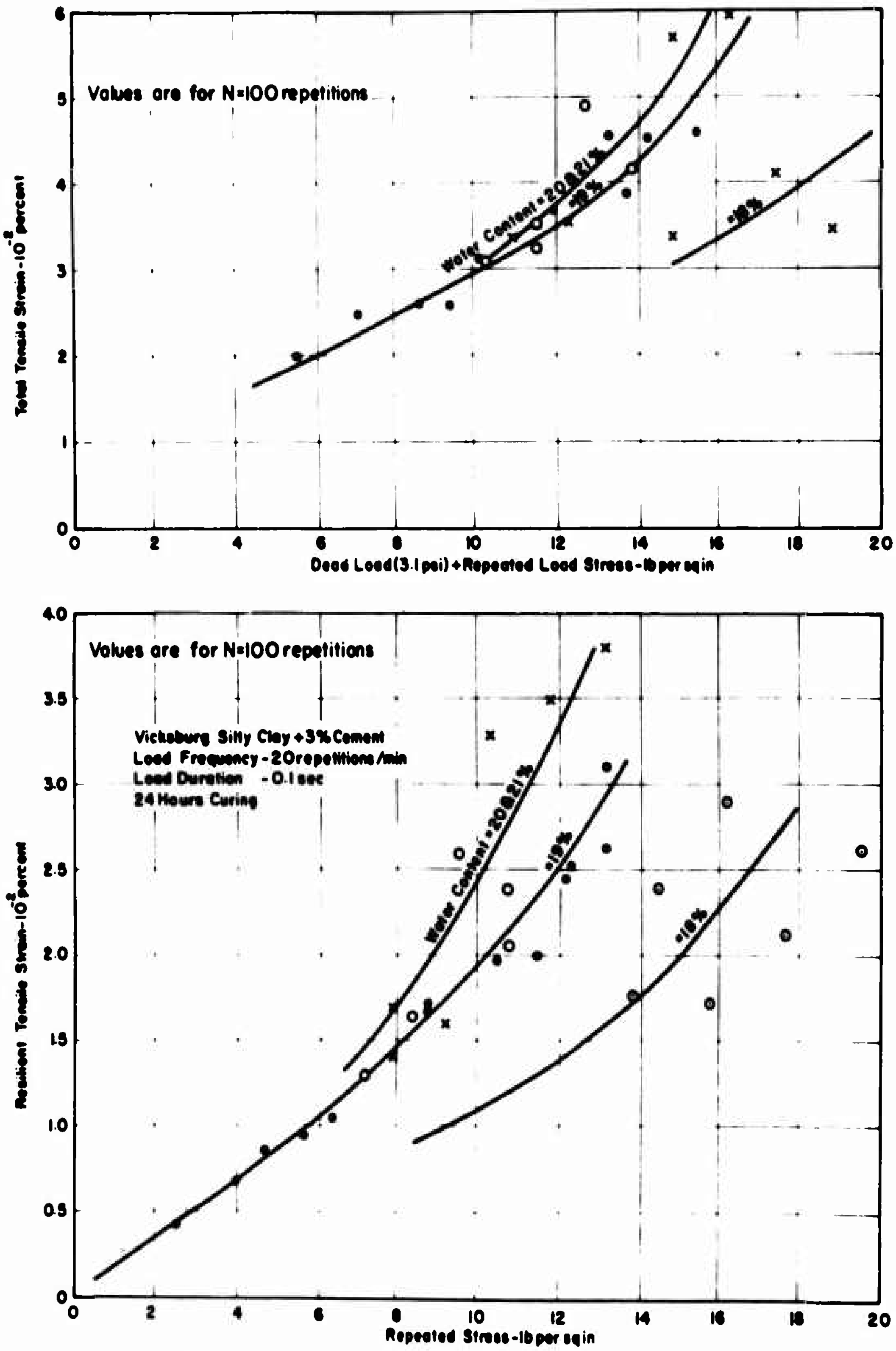
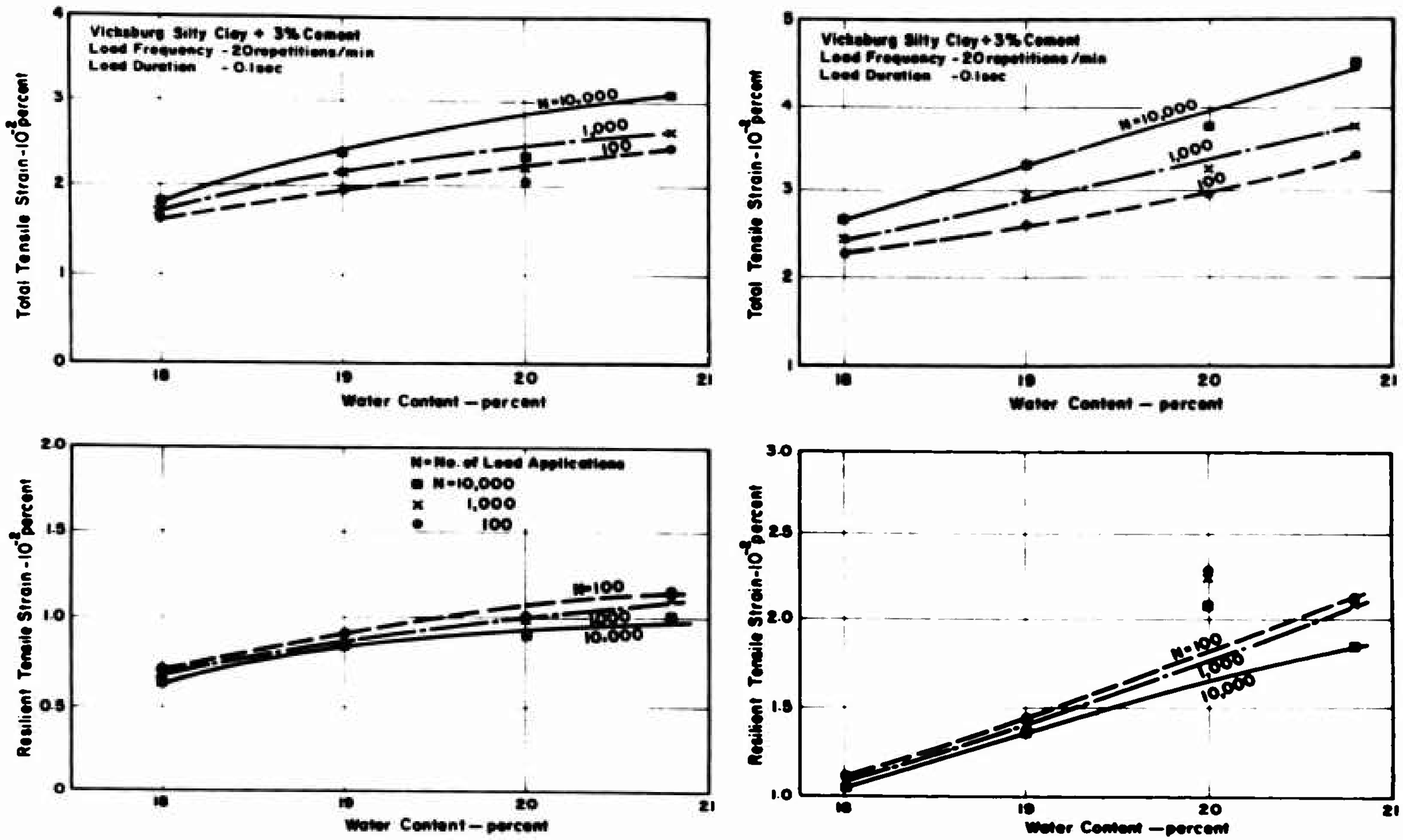


FIG.15- RESILIENT AND TOTAL STRAINS AS A FUNCTION OF FLEXURAL STRESS FOR BEAM SPECIMENS AT DIFFERENT WATER CONTENTS.



(a) Repeated Stress = 5 lb per sq in

(b) Repeated Stress = 8 lb per sq in

FIG.16 — RESILIENT AND TOTAL STRAINS AS A FUNCTION OF WATER CONTENT AT FLEXURAL STRESSES OF 5 AND 8 PSI.

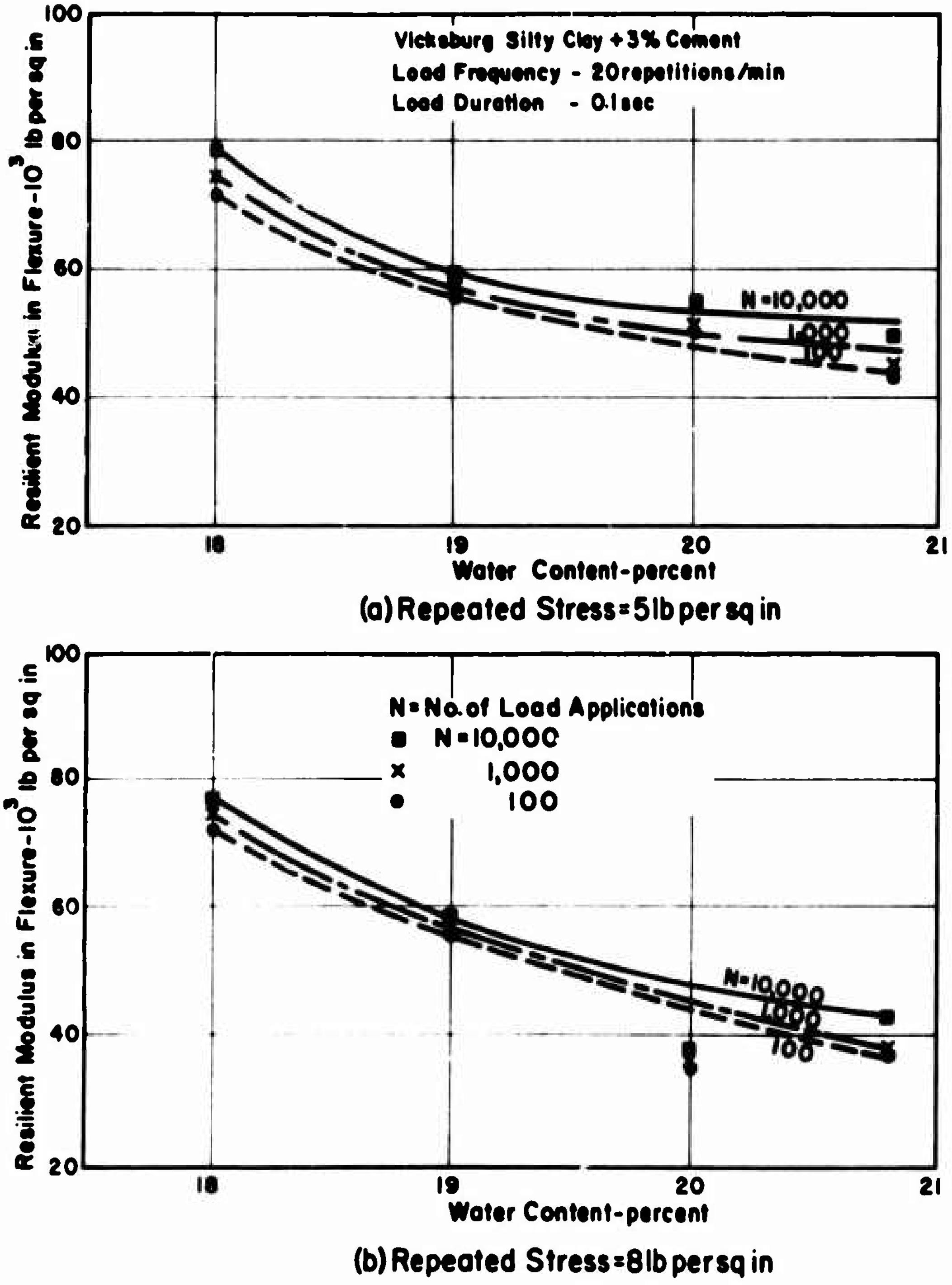


FIG. 17— RESILIENT MODULUS IN FLEXURE AS A FUNCTION OF WATER CONTENT FOR CEMENT-TREATED SILTY CLAY.

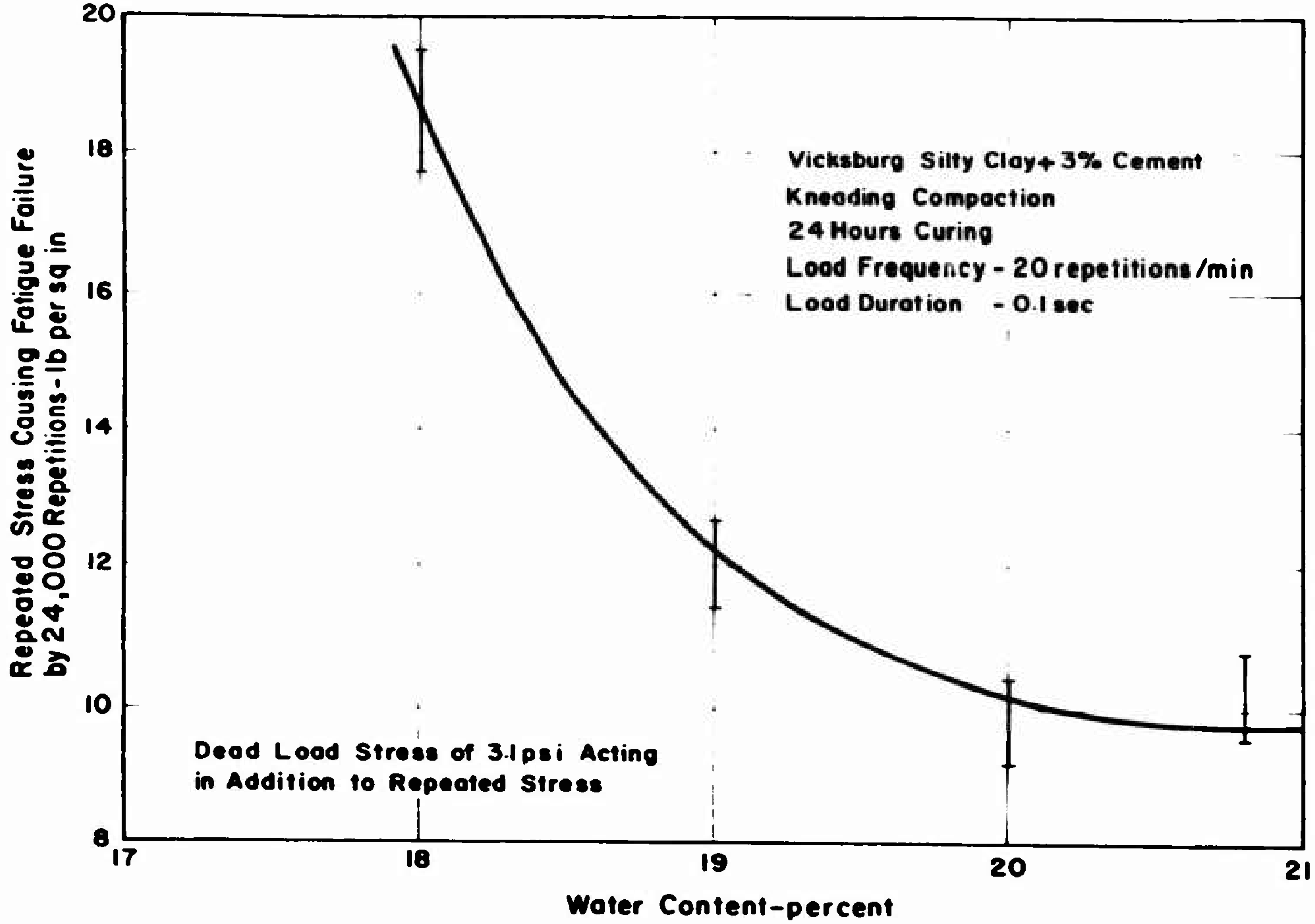


FIG.18— REPEATED FLEXURAL STRESS TO CAUSE FATIGUE FAILURE WITHIN 24,000 LOAD APPLICATIONS.

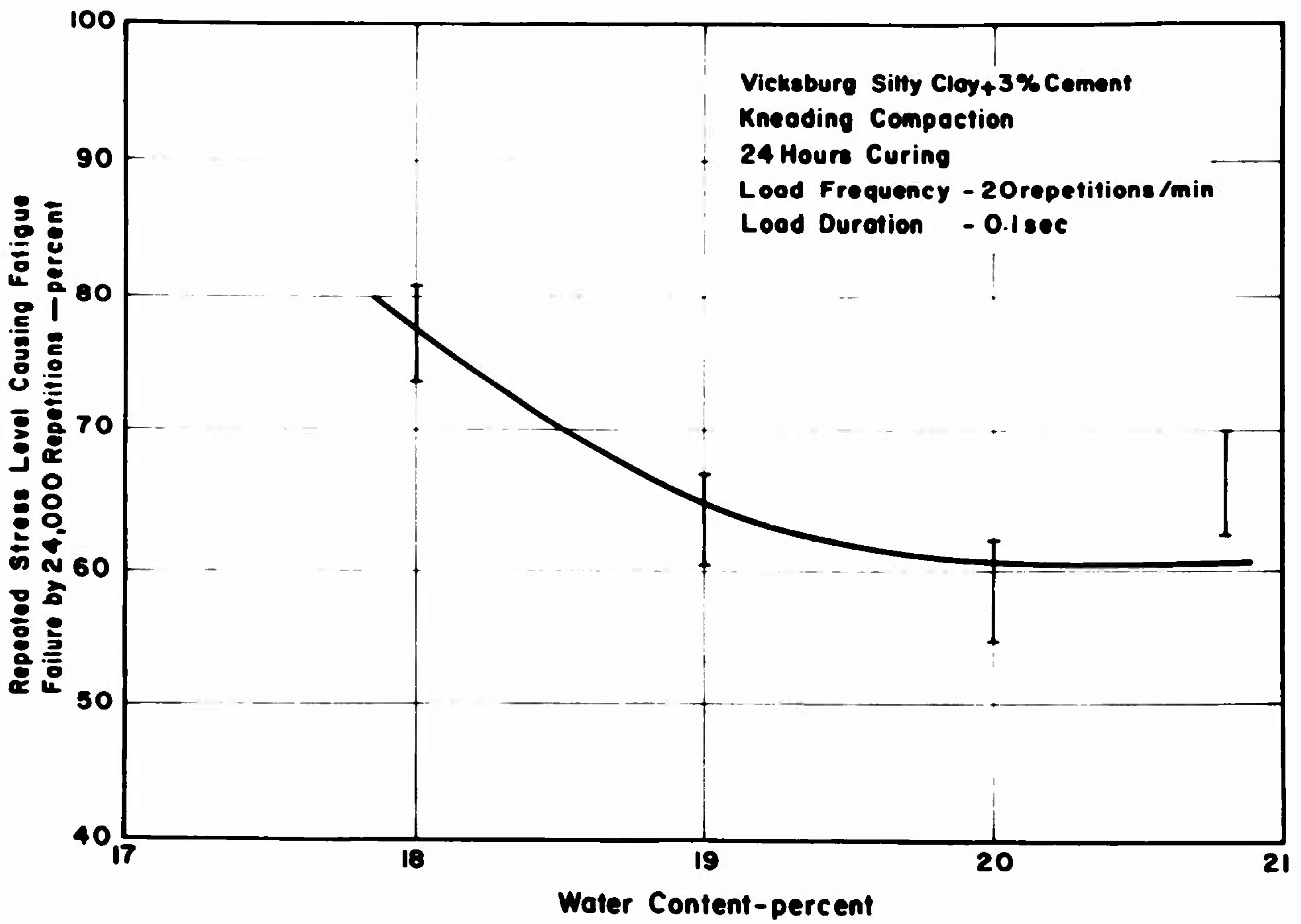


FIG.19— REPEATED FLEXURAL STRESS LEVEL TO CAUSE FATIGUE FAILURE WITHIN 24,000 LOAD APPLICATIONS.

Effect of Curing Time on Behavior in Repeated Flexure

All of the repeated flexure results presented thus far have been obtained for specimens cured for 24 hours prior to loading. To investigate the effects of curing time a test series was also performed on specimens cured for periods of one to six days prior to loading. A repeated load stress of 60 percent of the strength at the start of repeated loading was used. Strength and strain at failure characteristics of cement-treated silty clay after various curing periods have been shown previously in Fig. 10. From this figure it is apparent that the longer the curing period prior to repeated loading the higher the actual stress applied.

The variation of total, resilient, and permanent plastic strains with curing time after 100, 1,000, and 10,000 load repetitions is shown in Fig. 20. In all cases the results show that increased curing time results in decreased strain in spite of the fact that the applied stress increases with curing time and the effect, as would be expected, is most pronounced at the shortest times.

As a stress level of 60 percent was the only loading condition investigated no data are available concerning the effect of curing time on fatigue. None of the specimens tested failed within the 24,000 repetitions to which they were subjected. Since increased curing time results in increased brittleness as well as higher strength (Fig. 10), the probability of fatigue may increase with age. Further studies are needed on this problem. For the conditions studied, however, increased curing periods resulted in a marked increase in resilient modulus as may be seen in Fig. 21. Unfortunately scatter in the data make the curves somewhat uncertain at the longer times.

Effect of Repeated Flexure on Properties

The data have shown that if the repeated flexural stress and number of load repetitions are sufficiently large, then fatigue failure will develop. It is of interest in addition to examine the influence of repeated flexural stresses on cement-treated silty clay in those cases where the beams did not fail.

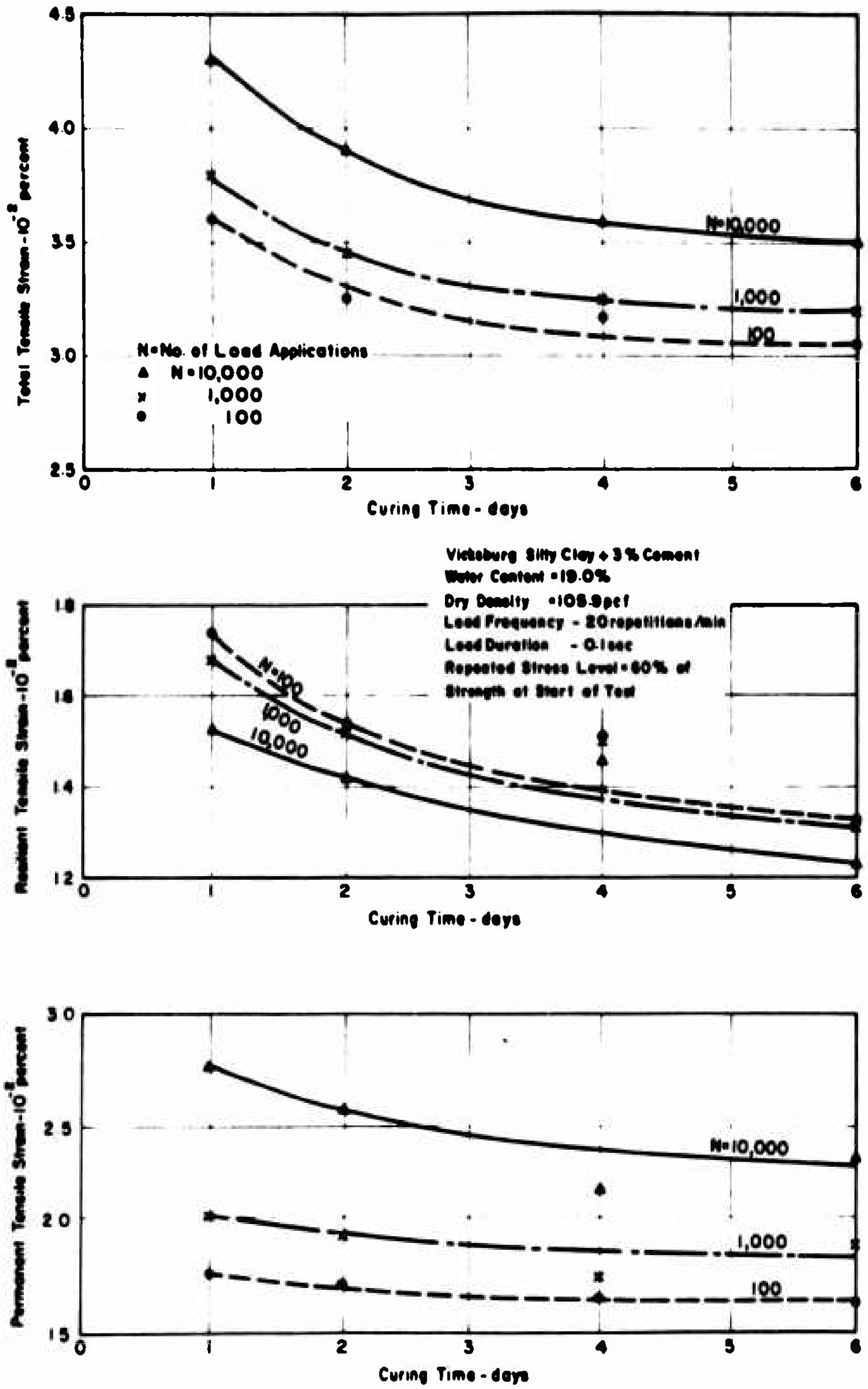


FIG 20 – EFFECT OF CURING PERIOD ON STRAINS DURING REPEATED FLEXURE.

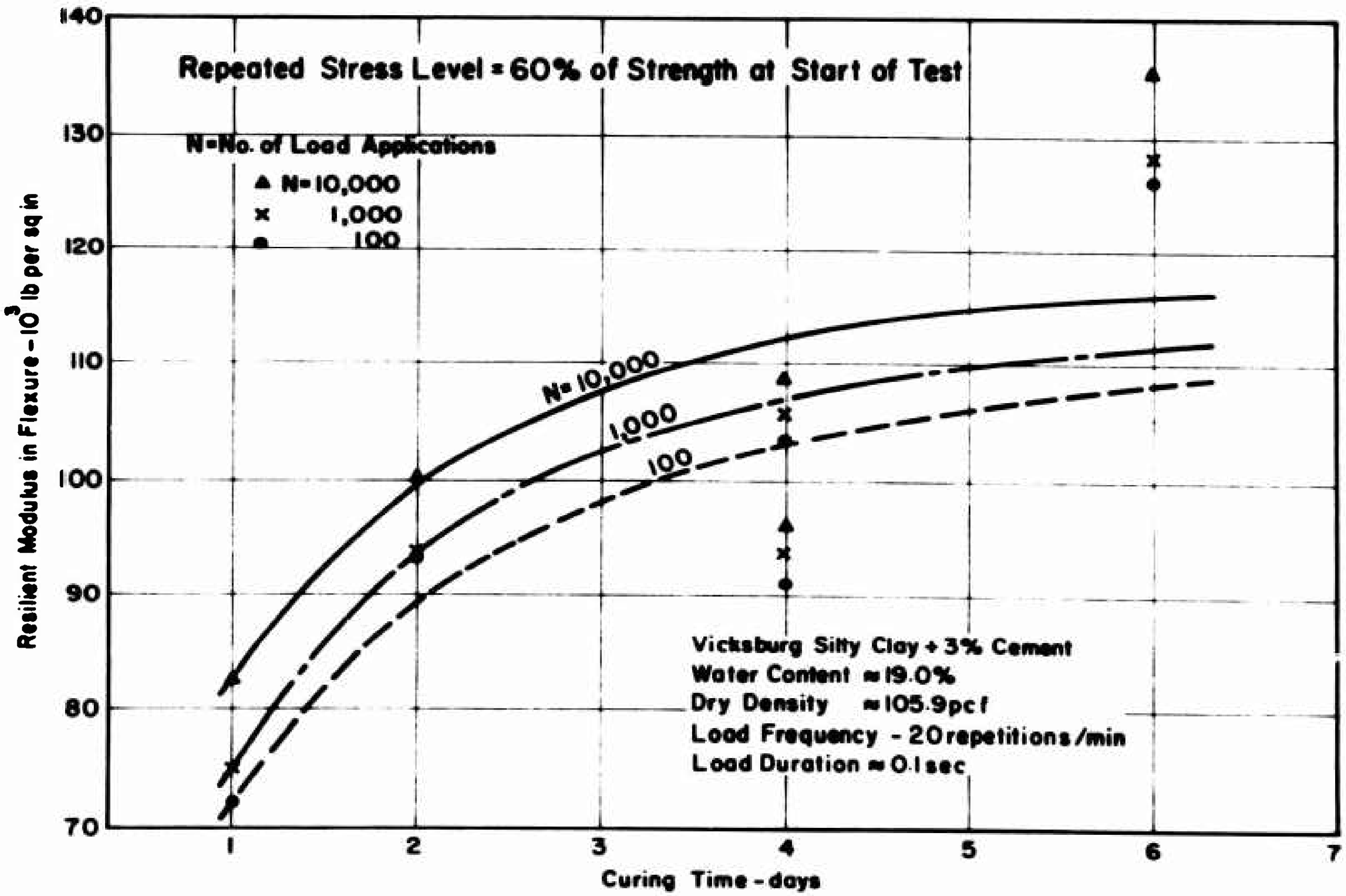


FIG.21— EFFECT OF CURING PERIOD ON RESILIENT MODULUS IN FLEXURE.

Fig. 22 presents the relationship between flexural strength (in static tests) after repeated loading as a function of repeated stress level. The value shown for 0 percent repeated stress level is the average for three identical samples not subjected to repeated loading but tested at the same age as corresponding specimens after repeated loading. Also shown in Fig. 22 is the variation of strain at failure in static tests after repeated loading as a function of repeated stress level. While there is considerable scatter in the results, which is not surprising in view of the abrupt nature of failure in this type of test, it is clear from Fig. 22 that repeated loading results in an increase in flexural strength and decrease in strain at failure.

Further evidence of flexural strength increases as a result of flexural repeated flexural stress is provided by Fig. 23. Curves are shown for strengths of beam specimens cured for 24 and 44 hours as a function of water content, and for specimens subjected to 24,000 load repetitions of a stress equal to 50 percent of the flexural strength at the start of the test. The age of these specimens at the time of the static strength test was 44 hours (24 hours for curing and 20 hours for application of the 24,000 load repetitions). Similar curves for strain at failure as a function of water content are also shown in Fig. 23.

The influence of curing time prior to repeated loading on strength after repeated loading is shown in Fig. 24. Again a strength increase is observed; its relative amount, however, appears to decrease somewhat with increase in curing period. This is not unreasonable, since the factors responsible for the strength increase should be more effective at early ages when the cement stabilized soil is more susceptible to changes in structure, water content distribution, density and other properties.

In view of the fact that definite fatigue characteristics were observed which were similar to those for other engineering materials subjected to repeated flexural stresses, it was somewhat surprising to find that the strength and stiffness of specimens not suffering fatigue failures were increased rather than decreased. A number of possible causes for these increases were investigated.

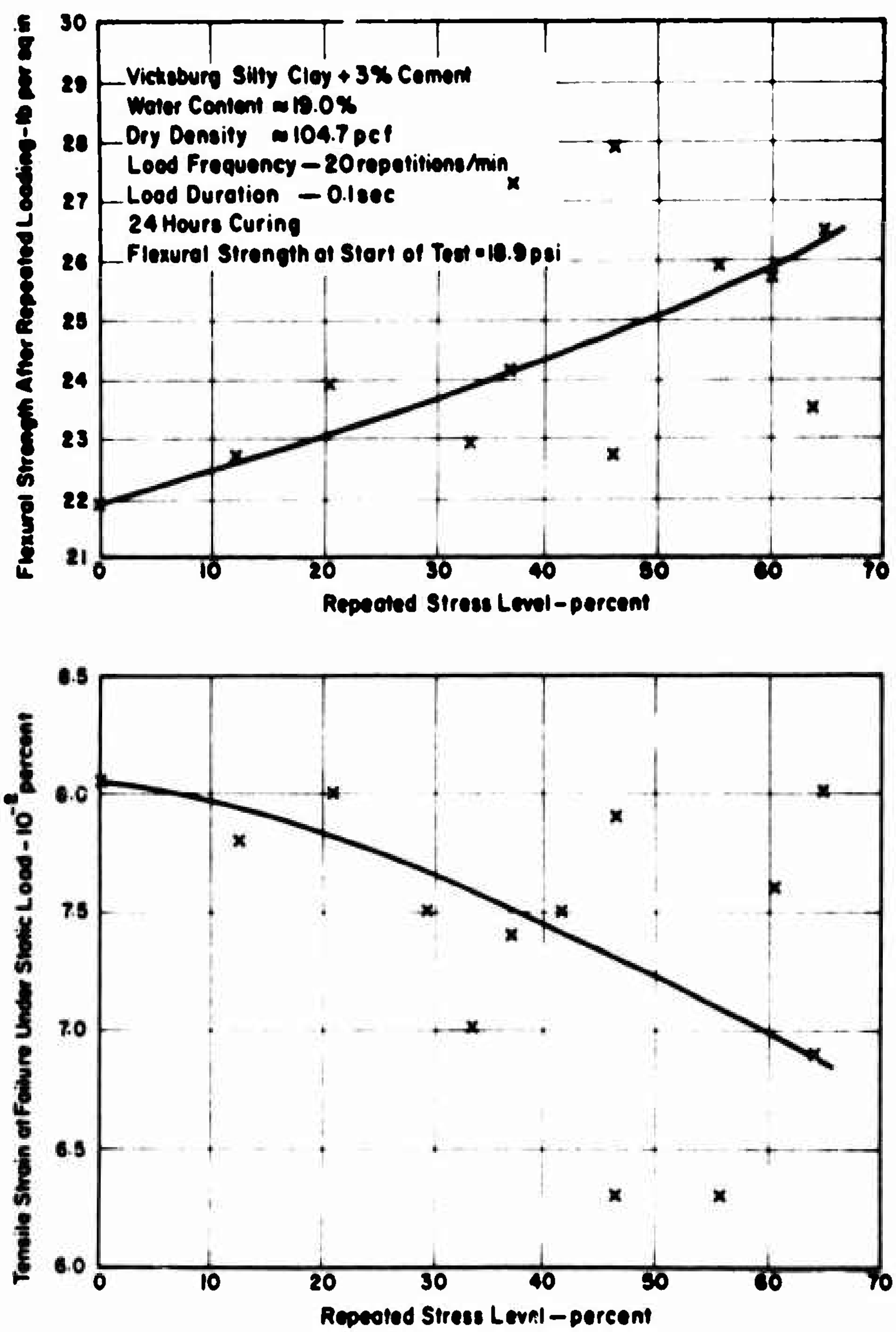


FIG. 22 — FLEXURAL STRENGTH AND STRAIN AT FAILURE AFTER REPEATED LOADING AS A FUNCTION OF REPEATED STRESS INTENSITY.

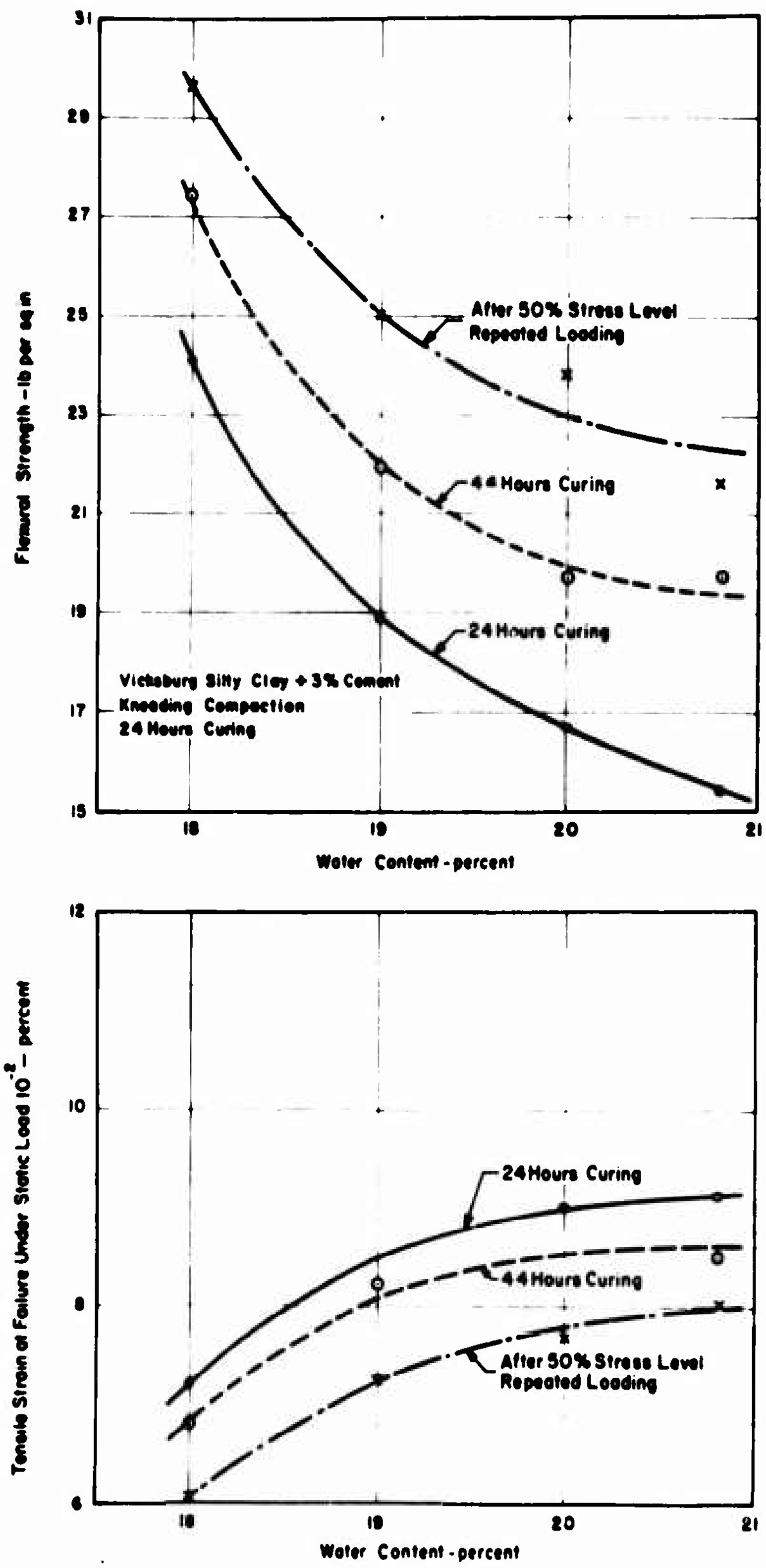


FIG.23 — STRENGTH AND STRAIN AT FAILURE AFTER REPEATED LOADING AS A FUNCTION OF WATER CONTENT.

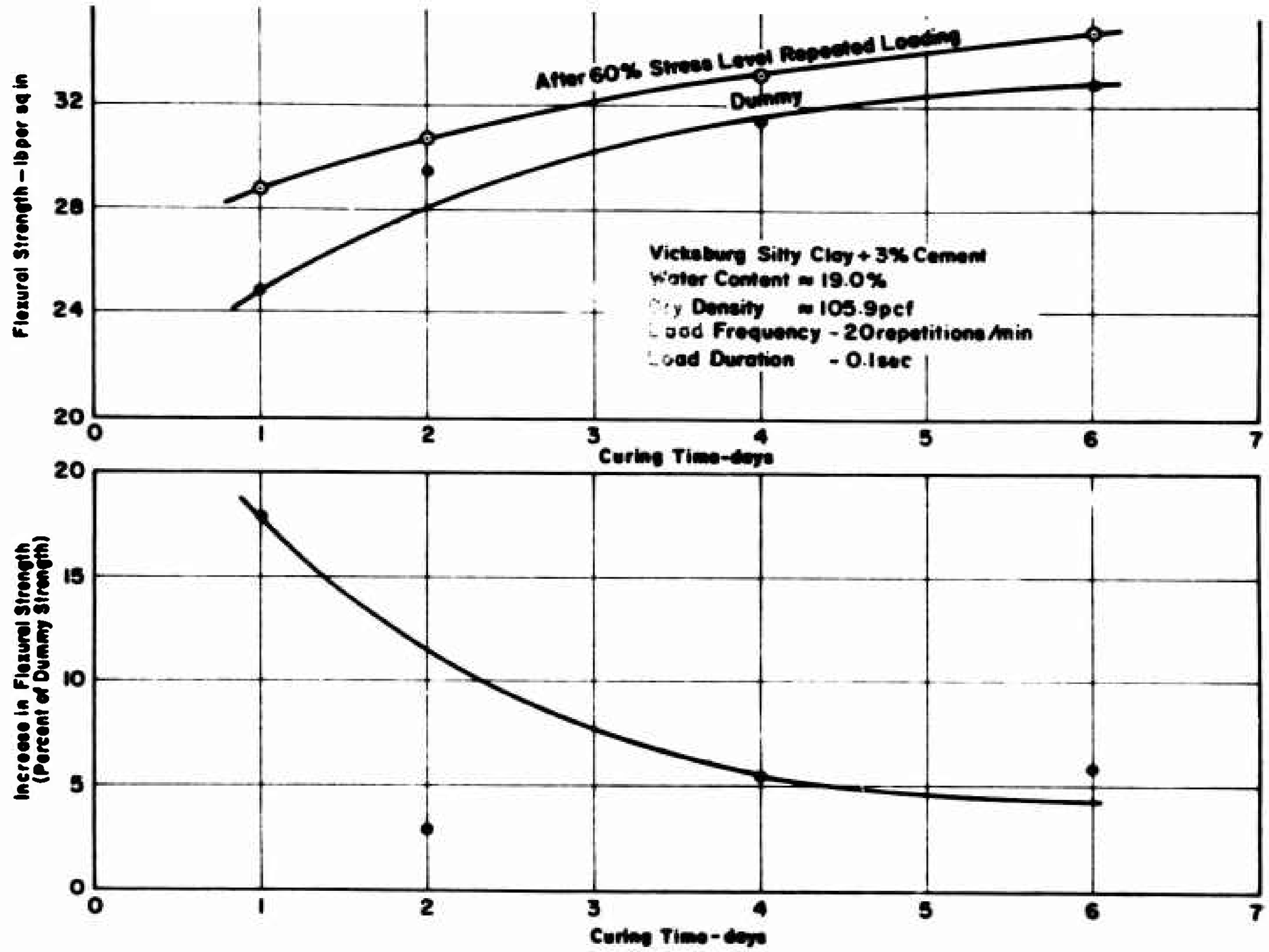


FIG.24 – EFFECT OF CURING TIME ON FLEXURAL STRENGTH AFTER REPEATED LOADING.

Consideration was given to the following possibilities.

1. Water content variations. In general the average water content of beam specimens decreased from 0.25 to 0.50 percent, depending on the initial water content, between compaction and the end of the test. There was no significant difference, however, between samples subjected or not subjected to repeated loading. It was found that the water content of the material above the neutral axis of the beams was about 0.2 to 0.3 percent greater than that for the material below the neutral axis. There was no significant difference in this water content variation for dummy and repeated load specimens. Thus water content variations appear inadequate to explain the strength increases due to repeated loading.

2. Density variations. An attempt was made to determine whether or not density variations developed within the beams as a result of repeated loading by trimming small samples from a beam at the end of the test. No significant variations were noted.

3. Variation in strength across the beam cross section. Limited data showed that the compressive strength of specimens trimmed from the zone above the neutral axis was slightly less than that of specimens from below the neutral axis for beams subjected to repeated loading. No conclusion could be drawn in the case of dummy specimens not subjected to repeated loading.

4. Dead load stress effects. The beam specimens were simply supported during repeated loading, and thus they were subjected to a continuous dead load flexural stress of about 3.1 psi throughout the test as noted earlier. Some evidence was obtained that this condition could account for some increase in strength and strain at failure over specimens not subjected to the stress as shown in Fig. 25. However, the strength increase due to this effect accounts for only a part of the total strength increase exhibited by specimens subjected to repeated load.

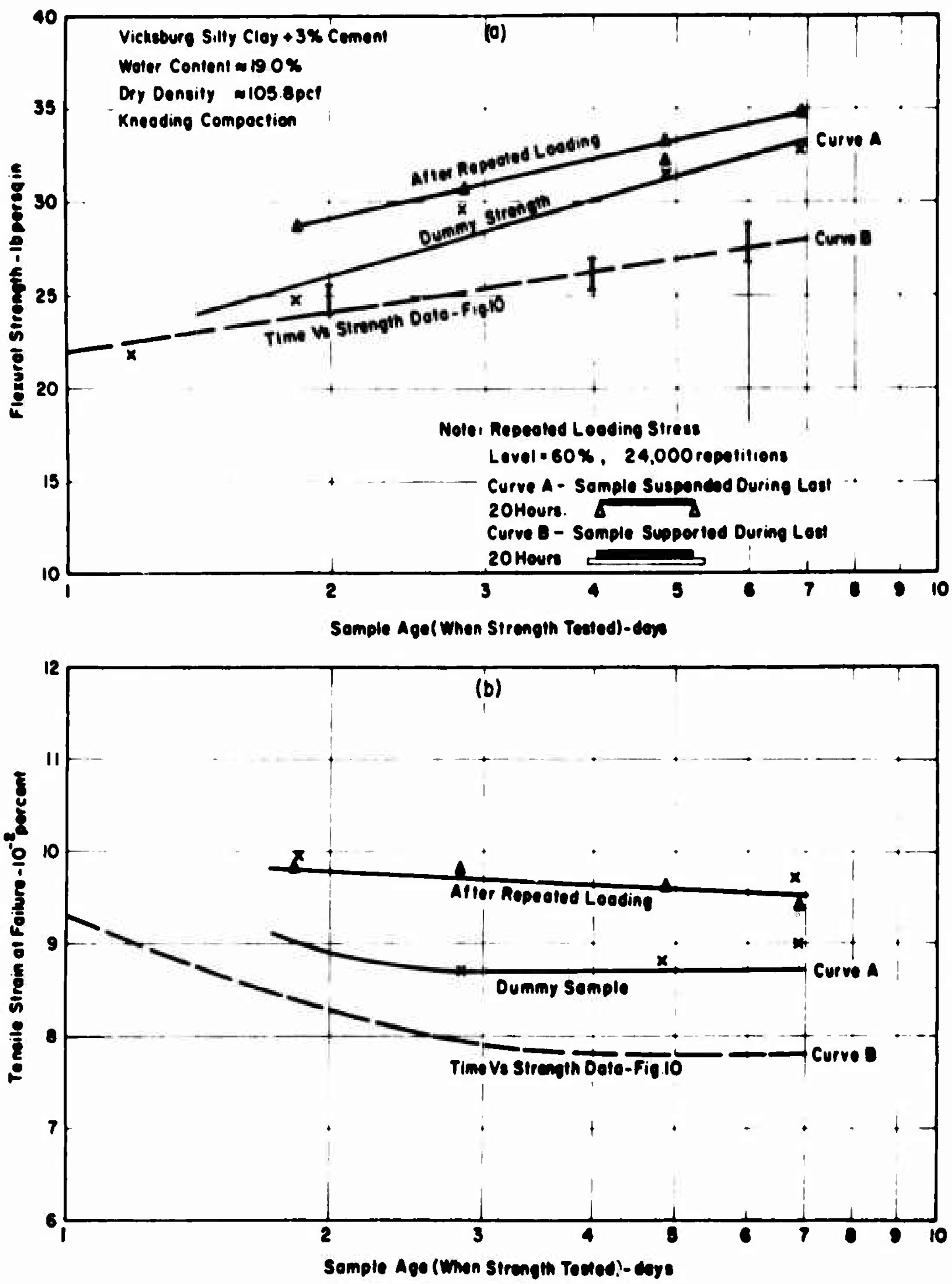


FIG 25 — EFFECT OF SUPPORT CONDITIONS, CURING TIME, AND REPEATED LOADING ON FLEXURAL STRENGTH.

It thus appears that repeated flexural stresses can cause measurable strength increases in the absence of fatigue failures.* The exact mechanism responsible for this stress increase is as yet unknown.

*Similar behavior has been observed for specimens of soil-cement, (Portland Cement Association, personnel communication).

IV. REPEATED LOAD FREQUENCY EFFECTS

Introduction

All repeated load test results presented in Report 1 and in this report thus far were obtained using a frequency of 20 repetitions per minute and duration of 0.1 sec. In the field, particularly in the case of military roads and airfields, frequency, duration, and magnitude of loadings are likely to be highly variable quantities depending upon the type, distribution and speed of traffic.

Reference to the operational characteristics for military roads and airfields in the theater of operations (Waterways Experiment Station Misc. Paper No. 3-605, 1963, and Report 1, Tables 1 and 2) indicates from 40 to 200 aircraft coverages applied in a period of 2 weeks to 6 months, and from 200 to 6150 vehicle passes in a period of 2 weeks to 6 months. Thus the frequency in the field is clearly much less than that used for the laboratory testing thus far. A frequency of 20 repetitions per minute was chosen for the laboratory test program primarily for convenience in required time of testing, since at this frequency a large number of repetitions can be applied in a short period of time. Furthermore, since those loadings were applied early in the life of the stabilized soil and since the strength of the treated soils increases with age the results should be conservative. On the other hand this approach cannot account for the detrimental effects associated with cracking due to increased brittleness, shrinkage, and temperature effects that may be significant in the field. Unfortunately a reliable assessment of these effects probably cannot be made on laboratory size specimens regardless of the loading conditions.

Recognizing these latter limitations the effects of frequency on behavior of stabilized silty clay in repeated load compression and flexure tests have been investigated and the results are described in this section.

Effect of Frequency on Behavior in Repeated Compression

Frequency effects were studied using silty clay stabilized with 3 percent cement compacted to a dry density of 104.5 pcf at a water content

of 19 percent and cured for 24 hours prior to the start of loading. A load duration of 0.1 sec. was used and compressive stresses ranging from about 5 to over 100 percent of the compressive strength at the start of loading were applied. Repeated load frequencies of 2, 10, and 20 repetitions per minute were used. All tests were continued to 24,000 load repetitions unless failure occurred sooner.

Fig. 26 compares total strains versus number of load repetitions at frequencies of 2 and 20 per minute. Fig. 27 shows the same comparison for resilient strains. It may be seen that while the total strain behavior is comparable in form at the two frequencies, the resilient strains decrease to much smaller values at large numbers of repetitions for low frequencies than for high frequencies. The increased age and thus the greater time available for curing at low frequencies is probably responsible for this reduction since at the end of 24,000 repetitions samples subjected to 2 repetitions per minute were about 6 days old; whereas, those subjected to 20 repetitions per minute were only 2 days old.

The effect of repeated loading frequency on total strain for 100, 1,000 and 10,000 load repetitions is shown in Fig. 28 for repeated load stress levels of 40, 60, and 80 percent. This figure shows that total strains decrease and that influence of load repetitions diminishes with decreasing frequency. Both of these observations are consistent with the increased strength and rigidity that can develop during the longer test period for the low frequency tests.

A similar plot for resilient strains is presented in Fig. 29. In this figure it will be noted that the resilient deformation increases with increased frequency; however, above a frequency of 10 repetitions per minute the increase in resilience with increased frequency is much less than that for a change from 2 to 10 repetitions per minute.

The variation of resilient modulus with frequency for stress levels of 40 and 80 percent is shown in Fig. 30. Decreasing the frequency leads to significant increases in modulus, and the effect of number of load repetitions is much more significant at low frequencies than high. The reason for this behavior is apparent from the data presented in Fig. 27.

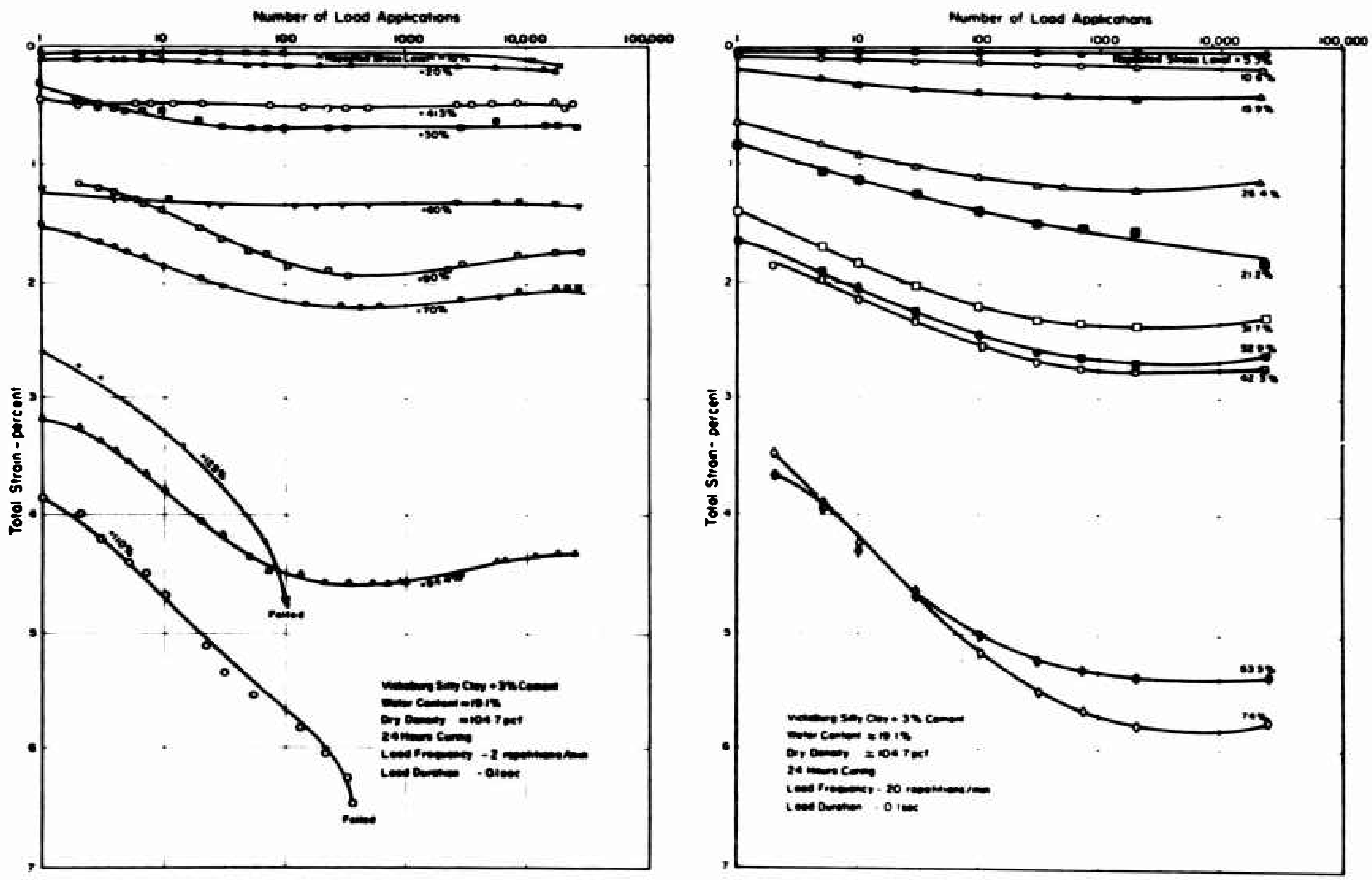


FIG. 26 TOTAL STRAIN VERSUS NUMBER OF LOAD APPLICATIONS FOR CEMENT TREATED VICKSBURG SILTY CLAY TESTED AT TWO FREQUENCIES

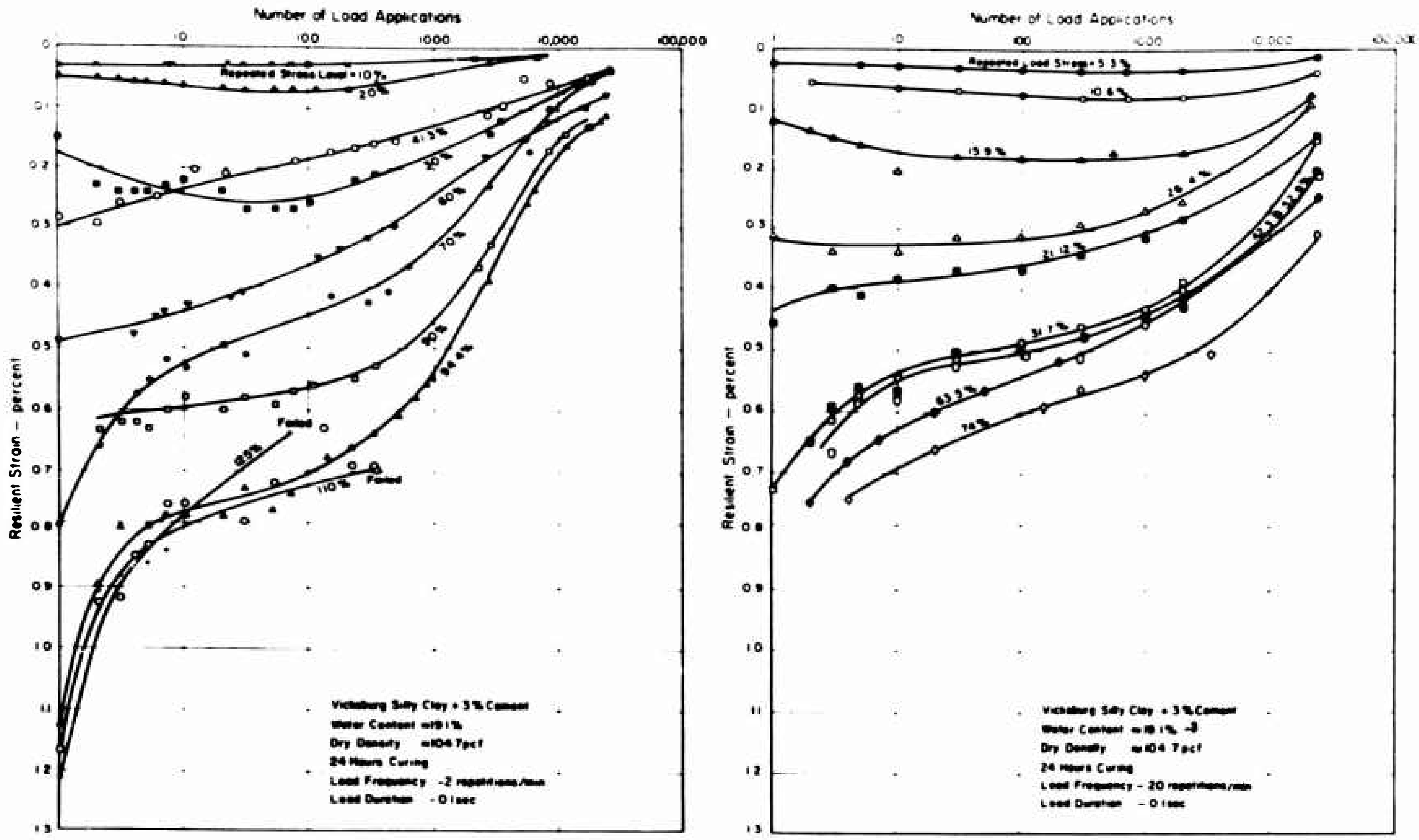


FIG. 27 RESILIENT STRAIN VERSUS NUMBER OF LOAD APPLICATIONS FOR CEMENT TREATED VICKSBURG SILTY CLAY TESTED AT TWO FREQUENCIES

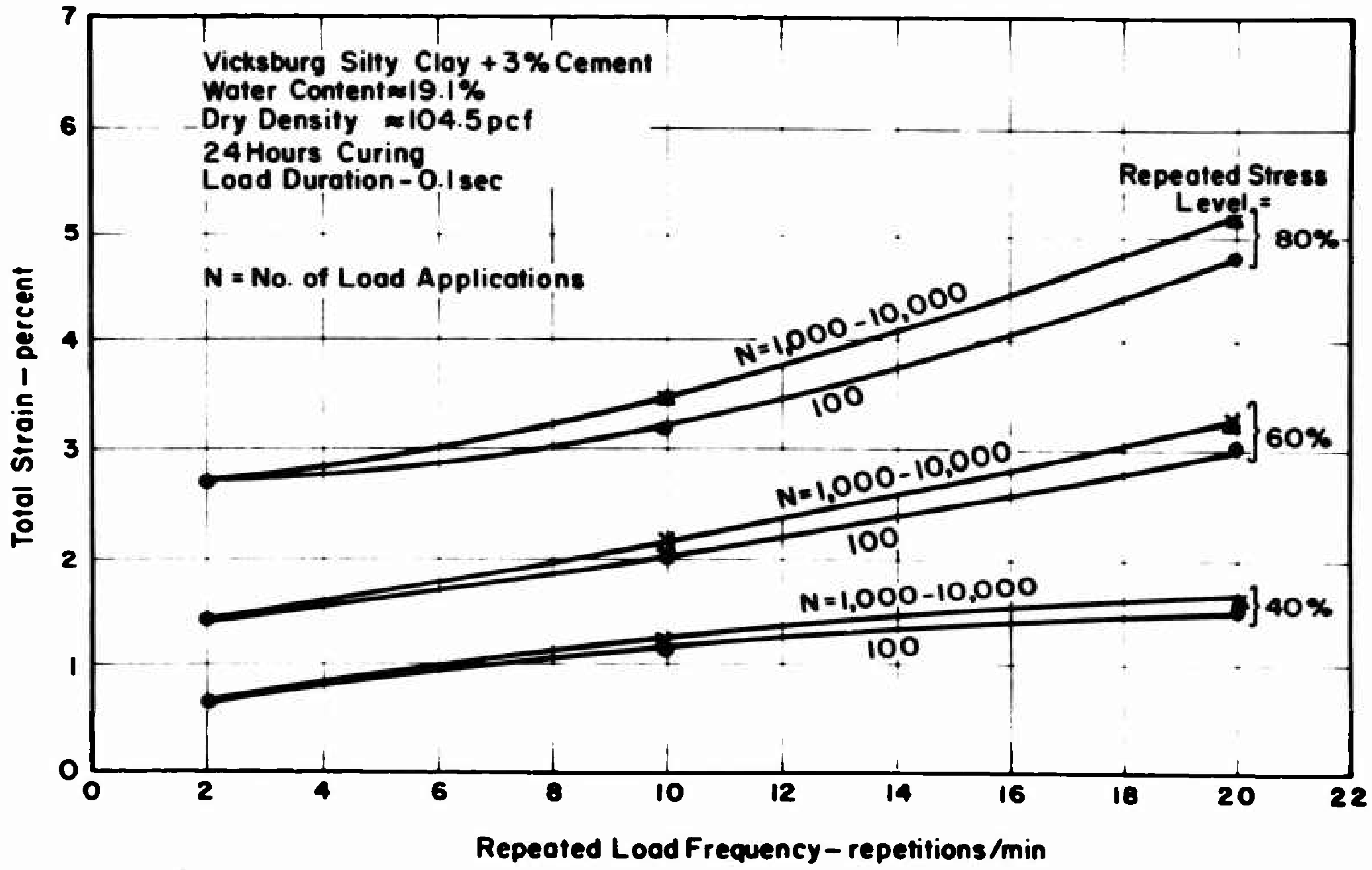


FIG. 28 — TOTAL COMPRESSIVE STRAIN AS A FUNCTION OF REPEATED LOADING FREQUENCY.

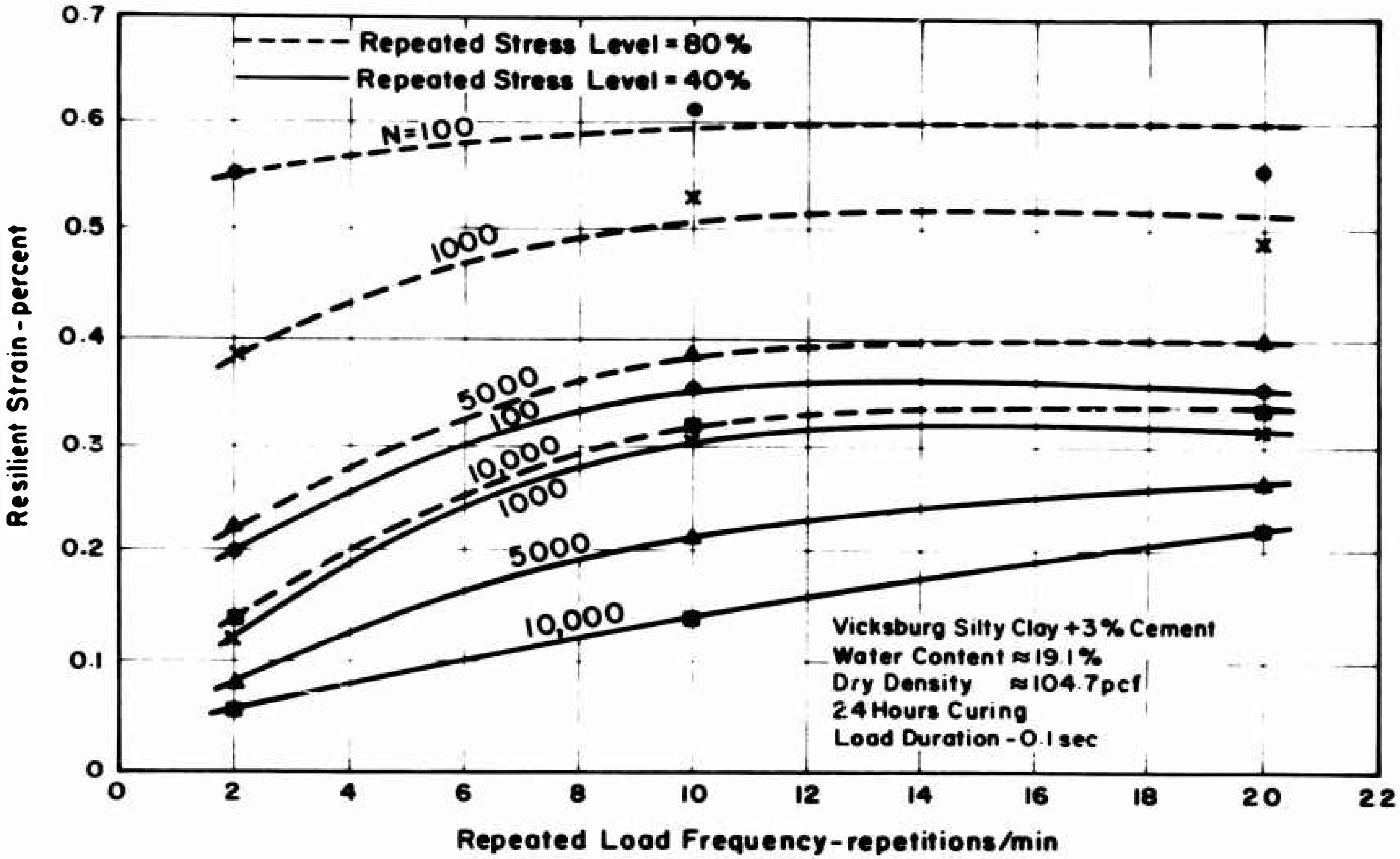
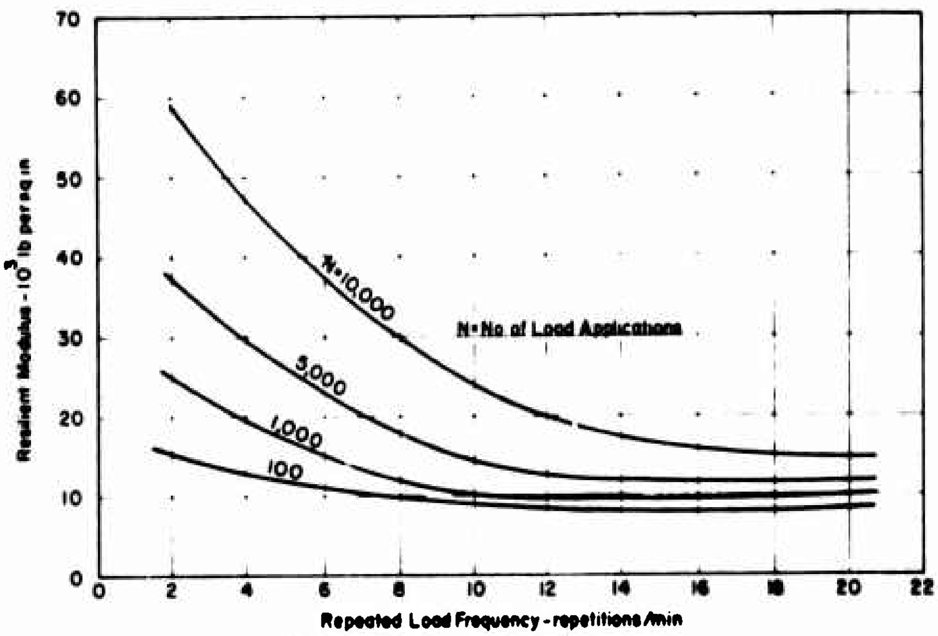
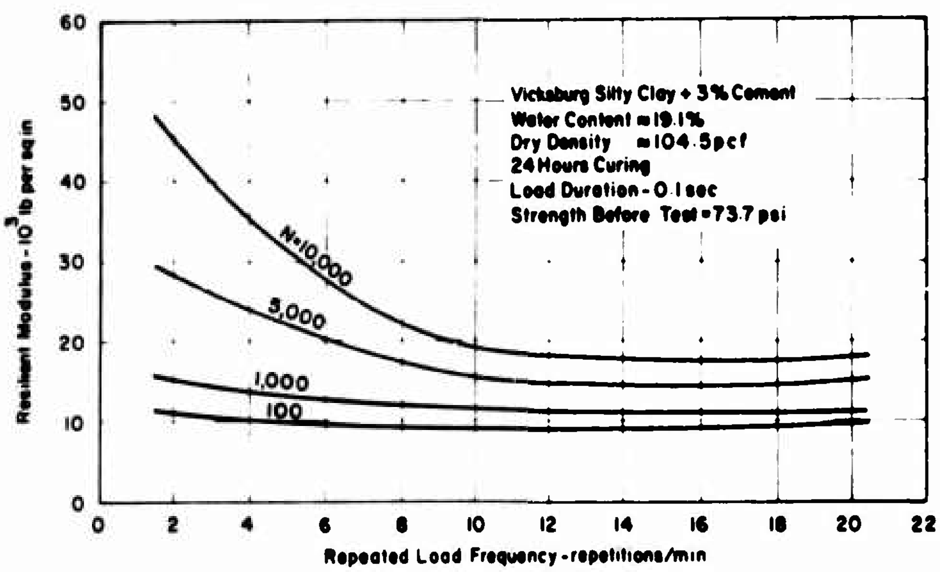


FIG. 29— RESILIENT COMPRESSIVE STRAIN AS A FUNCTION OF REPEATED LOADING FREQUENCY



(a) Repeated Stress Level = 40 percent



(b) Repeated Stress Level = 80 percent

FIG 30 - RESILIENT MODULUS IN COMPRESSION AS A FUNCTION OF FREQUENCY.

At a frequency of 2 repetitions per minute both the resilient strain at any stress level and the range of resilient strains for different stress levels decrease as the number of load repetitions increases.

The variation of resilient modulus in compression with stress level for frequencies of 2 and 20 cycles per minute is shown in Fig. 31. It may be noted that at the lower frequency the curves do not pass through a minimum at an intermediate stress level (except for N = 10,000) but decrease continuously with increasing stress. This behavior is similar to that for the buckshot clay (Fig. 5) and for silty clay-cement (13% cement). (Fig. 31, Report 1.) This result is consistent with the increased strength development associated with the frequency of 2 repetitions per minute as compared with 20 per minute. The fact that resilient modulus varies with frequency, as well as with type of loading (compression or flexure), stress intensity, and number of repetitions further complicates the problem of selection of appropriate values for use in analysis.

The effect of repeated compressive stress frequency on strength after repeated loading is shown in Fig. 32. The dummy strength curve refers to the strength of identical specimens at comparable ages but not subjected to repeated loading. It may be seen that the compressive strength is increased by repeated loading at all frequencies, and that the greater the stress intensity the greater the strength increase. In addition, the lower the frequency the greater the magnitude of the effect. Evidently the composite effect of strengthening due to slight densification or small decreases in average interparticle spacing at contact points, cement hydration, and the destructive effects of the repeated loads is such as to make low frequencies more favorable for strength increase.

Fig. 33 shows the variation of compressive strain at failure with repeated load frequency for samples tested at different stress intensities. The general tendency is for a slight decrease in failure strain with decrease in frequency and marked decrease in strain for increase in stress level for all frequencies.

Fig. 34 shows relationships between stress level and number of load repetitions in compression to cause fatigue failure for different frequencies. In only one case, a stress level of 97.5 percent and a

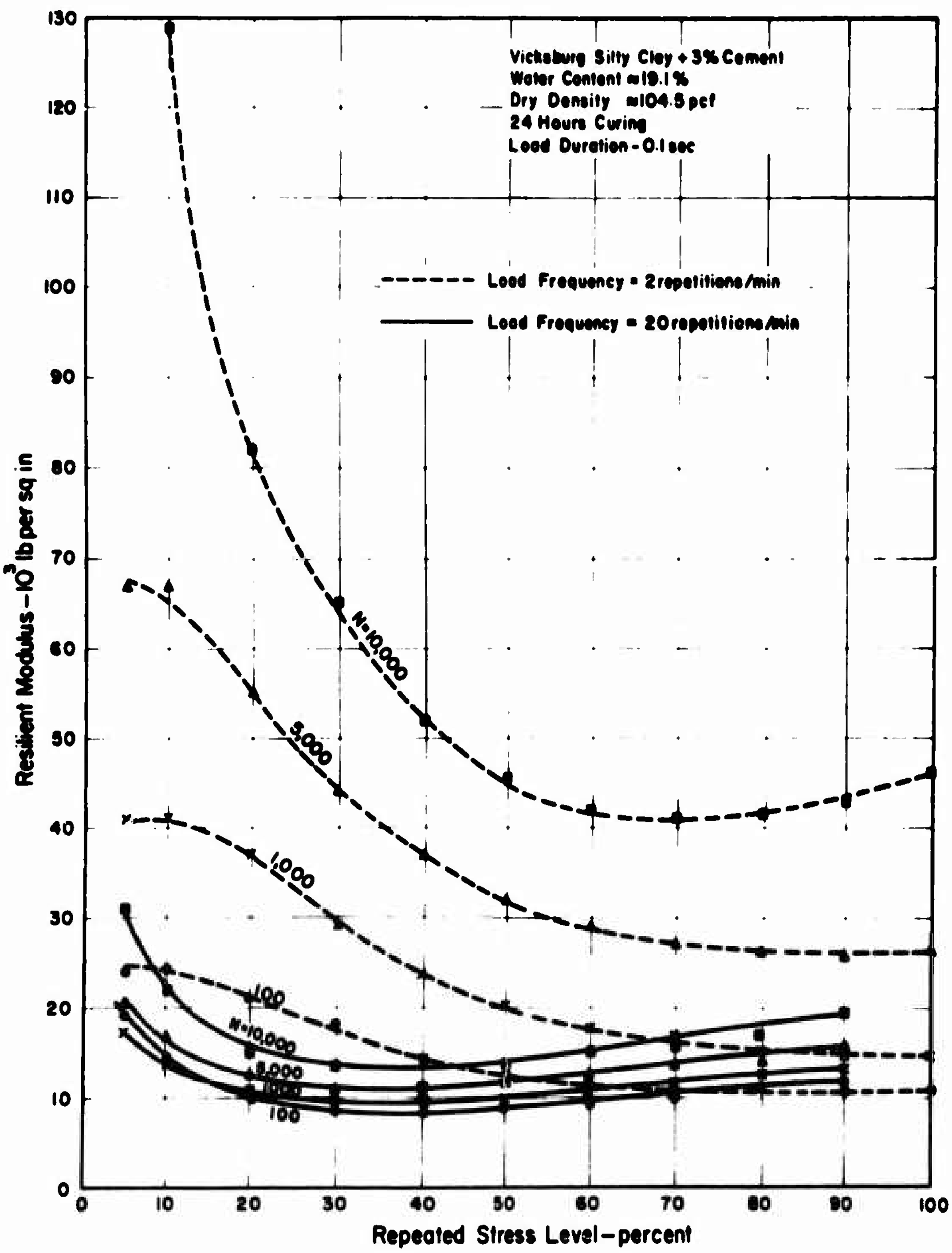


FIG.31 — RESILIENT MODULUS IN COMPRESSION AS A FUNCTION OF STRESS LEVEL FOR DIFFERENT FREQUENCIES.

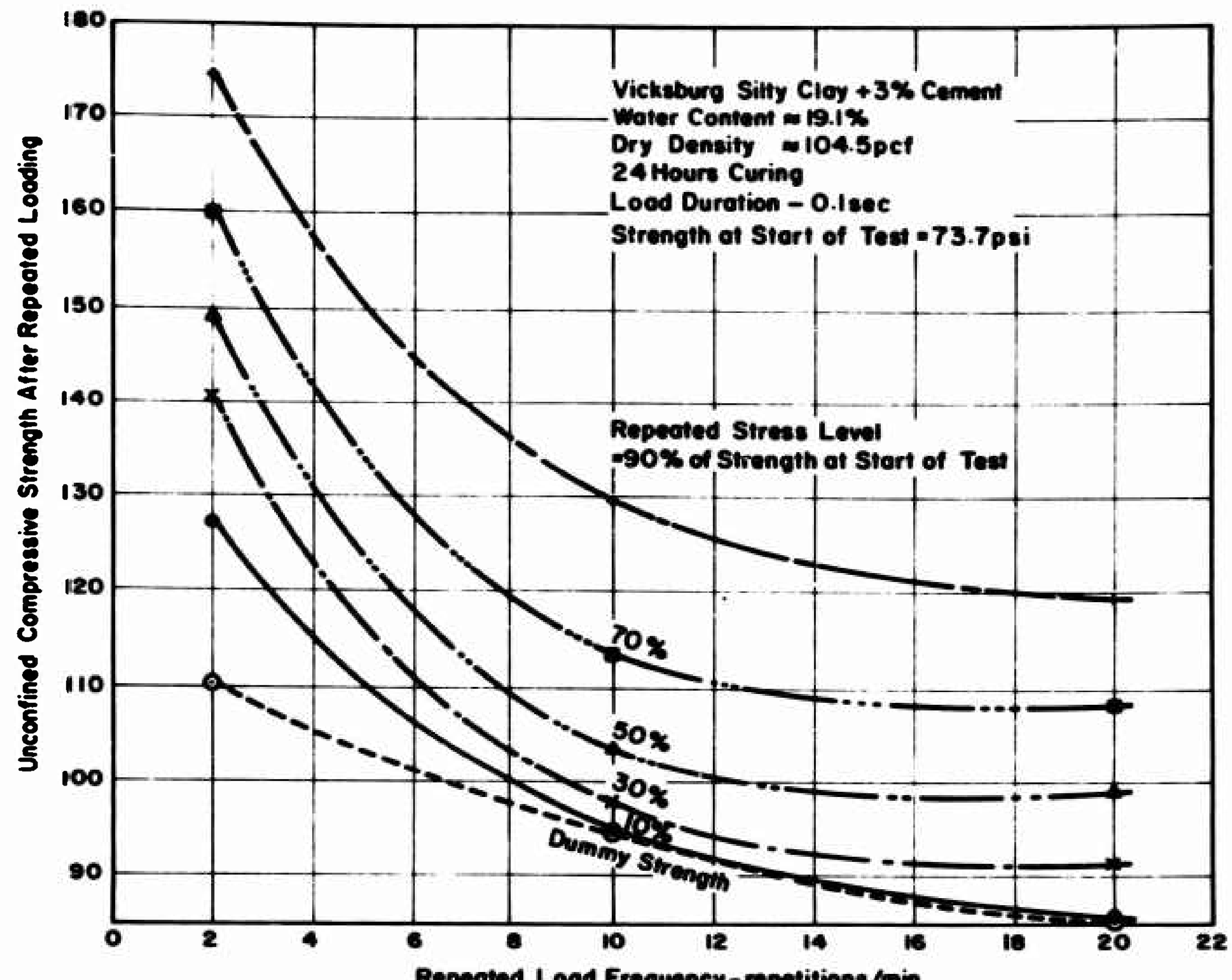


FIG.32 – COMPRESSIVE STRENGTH AFTER REPEATED LOADING AS A FUNCTION OF FREQUENCY.

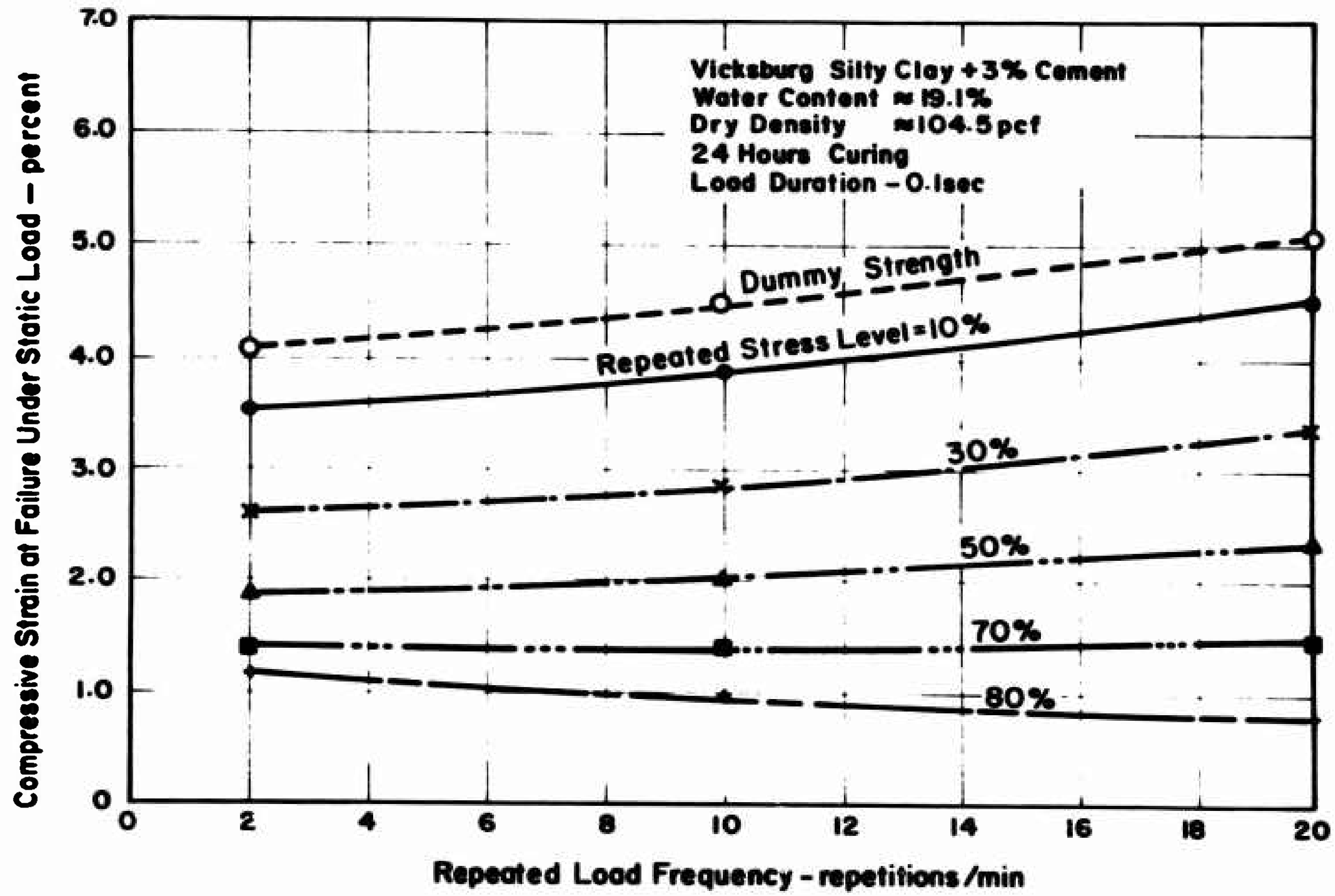


FIG.33— COMPRESSIVE STRAIN AT FAILURE AFTER REPEATED LOADING AS A FUNCTION OF FREQUENCY.

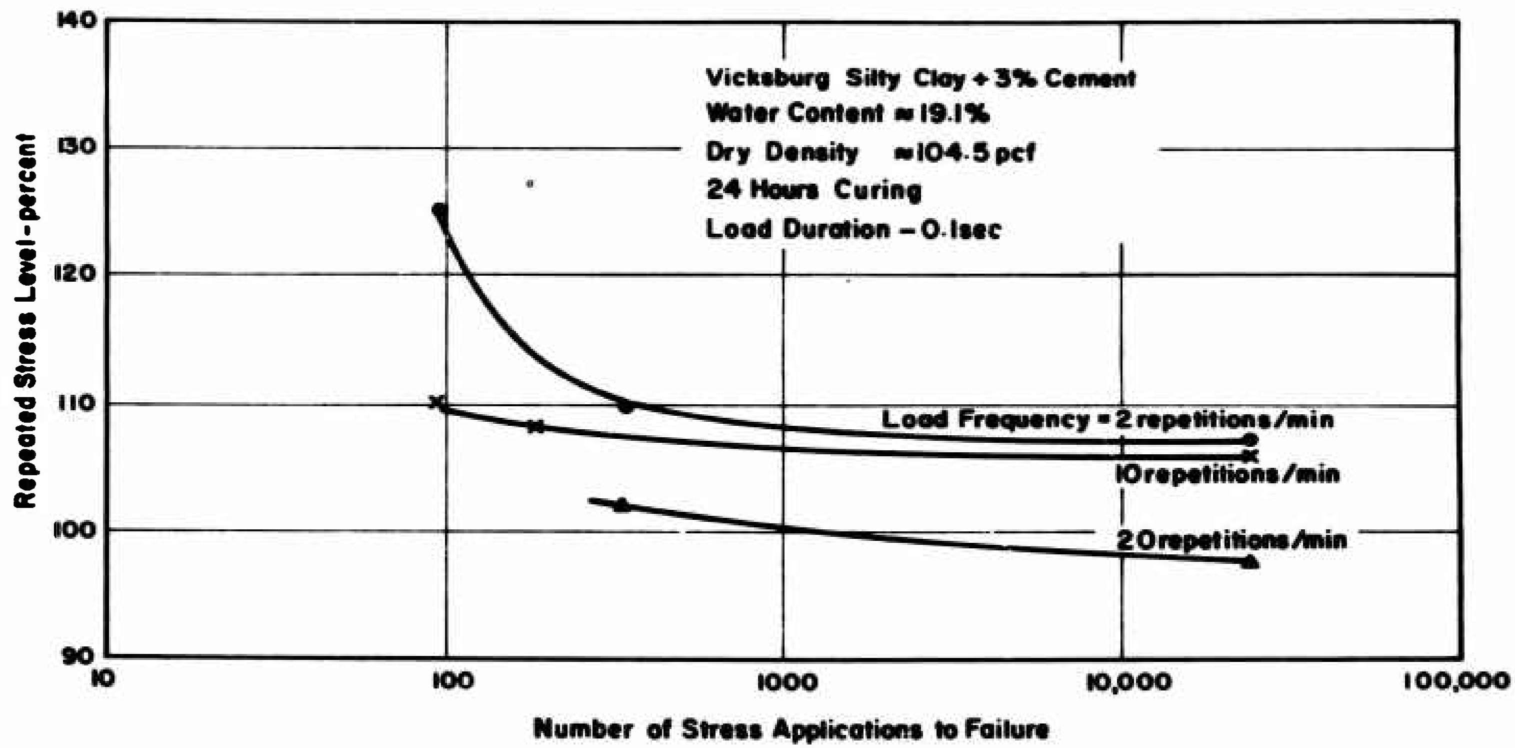


FIG.34 — REPEATED COMPRESSIVE STRESS LEVEL AS A FUNCTION OF NUMBER OF REPETITIONS TO FAILURE AT DIFFERENT FREQUENCIES.

frequency of 20 repetitions per minute, did fatigue occur at stress levels less than 100 percent of the initial strength. These results indicate that the lower the frequency the greater the stress level needed to cause fatigue failure. The additional period for curing resulting from lower frequencies is probably responsible for this effect.

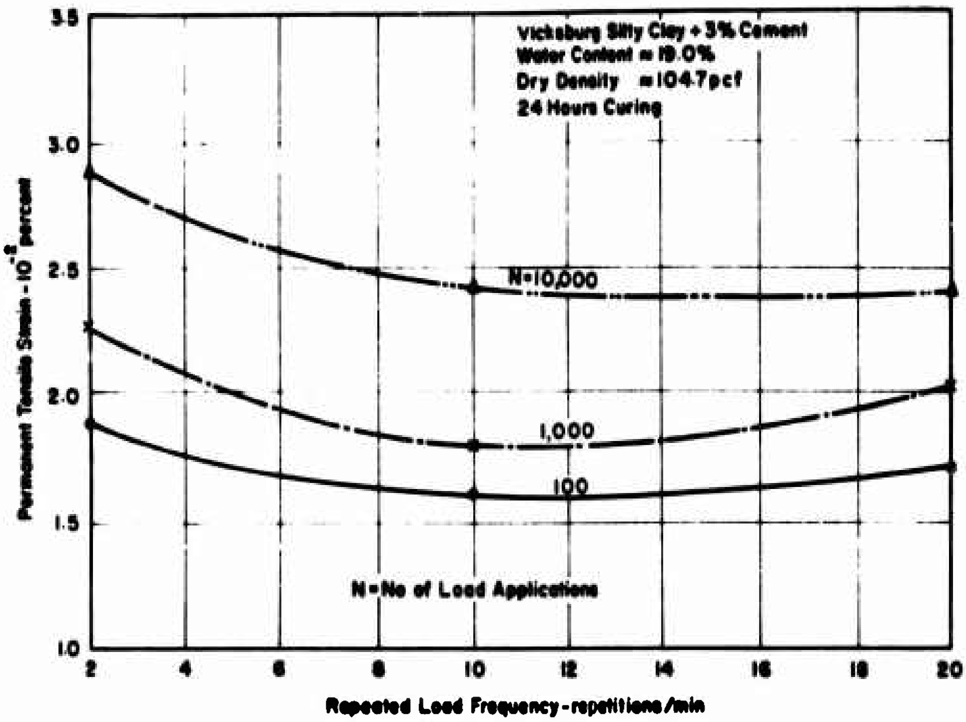
Effect of Frequency on Behavior in Repeated Flexure

Frequency effects in flexure were studied using beam specimens prepared to the same initial conditions as the cylindrical specimens used for frequency studies in compression. The variation of permanent deformation with frequency at different numbers of load repetitions is shown in Fig. 35 for two stress levels. It is somewhat surprising that the permanent deformations at low frequencies are slightly greater than at high frequencies. This apparent anomoly may have resulted from creep deformations under dead load stresses during the longer time required for the low frequency tests.

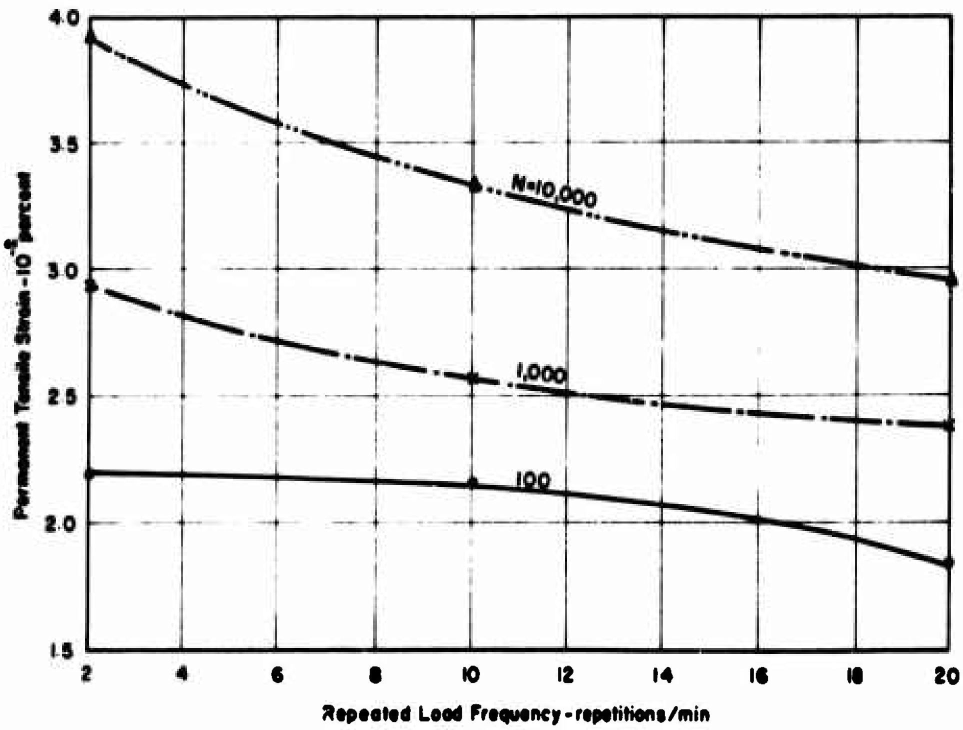
Values of resilient modulus in flexure as a function of frequency for different stress levels are shown in Fig. 36 for 100, 1000, and 10,000 load repetitions. After a large number of repetitions (10,000) the modulus is seen to decrease continuously with increasing frequency for all stress levels, and to decrease with increasing stress intensity. The effect of stress intensity is greatest at the lowest frequency. Thus the conclusion drawn previously from Fig. 13 and from tests on soil-cement (Report 1) that the resilient modulus in flexure is essentially independent of stress within the working range is seen not to be of general applicability.

The curves in Fig. 36 for 100 and 1000 load repetitions show that at the intermediate frequency of 10 repetitions per minute the resilient modulus may be higher than for either 2 or 20 repetitions per minute. The reason for this type of behavior is not apparent from the data obtained thus far.

Values of resilient modulus as a function of frequency after different numbers of load repetitions are shown in Fig. 37 for stress intensities of



(a) Repeated Stress Level = 25 percent



(b) Repeated Stress Level = 60 percent

FIG. 35 – PERMANENT DEFORMATION IN FLEXURE AS A FUNCTION OF FREQUENCY.

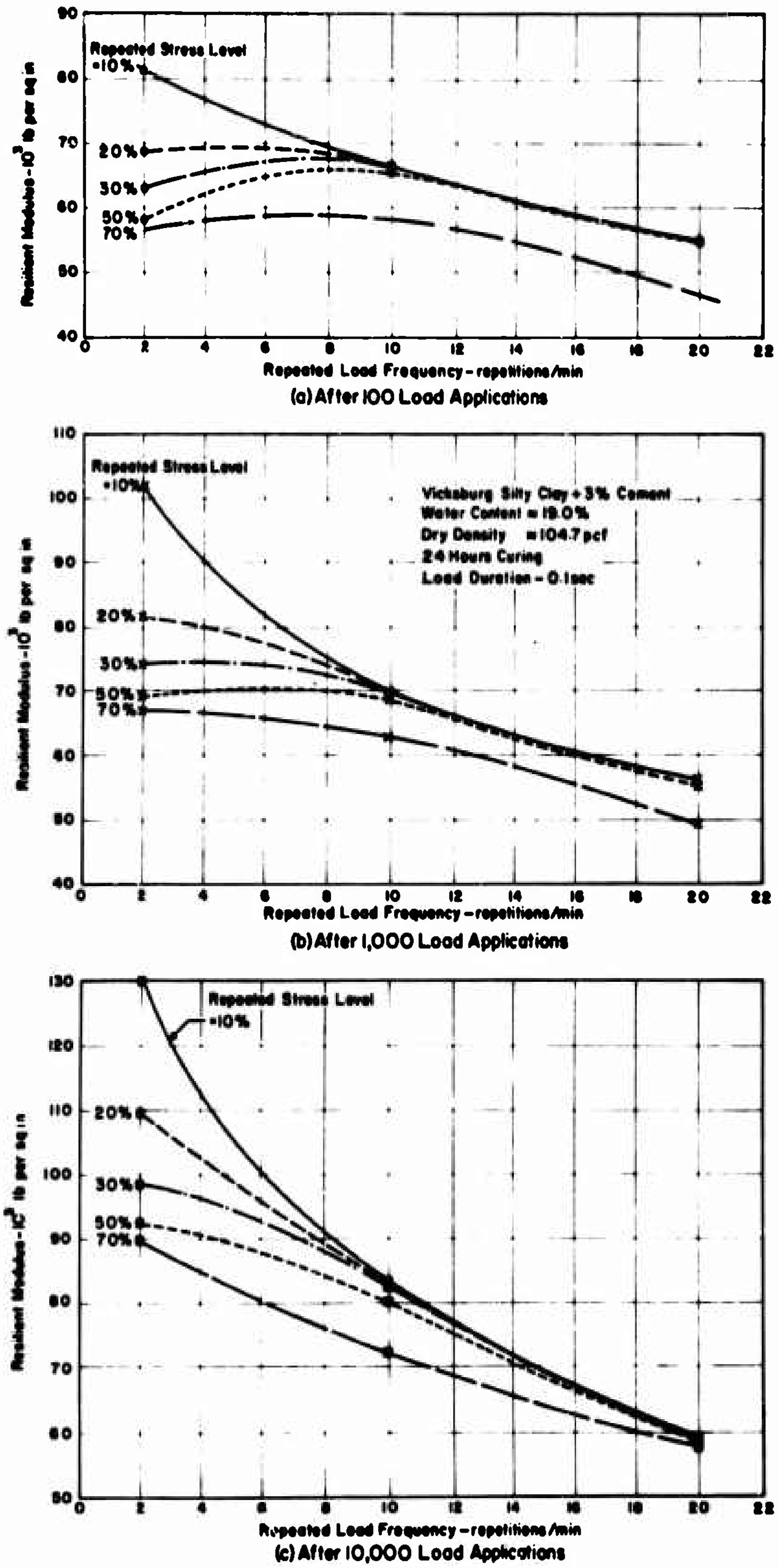


FIG. 36 – RESILIENT MODULUS IN FLEXURE AS A FUNCTION OF FREQUENCY FOR DIFFERENT STRESS LEVELS.

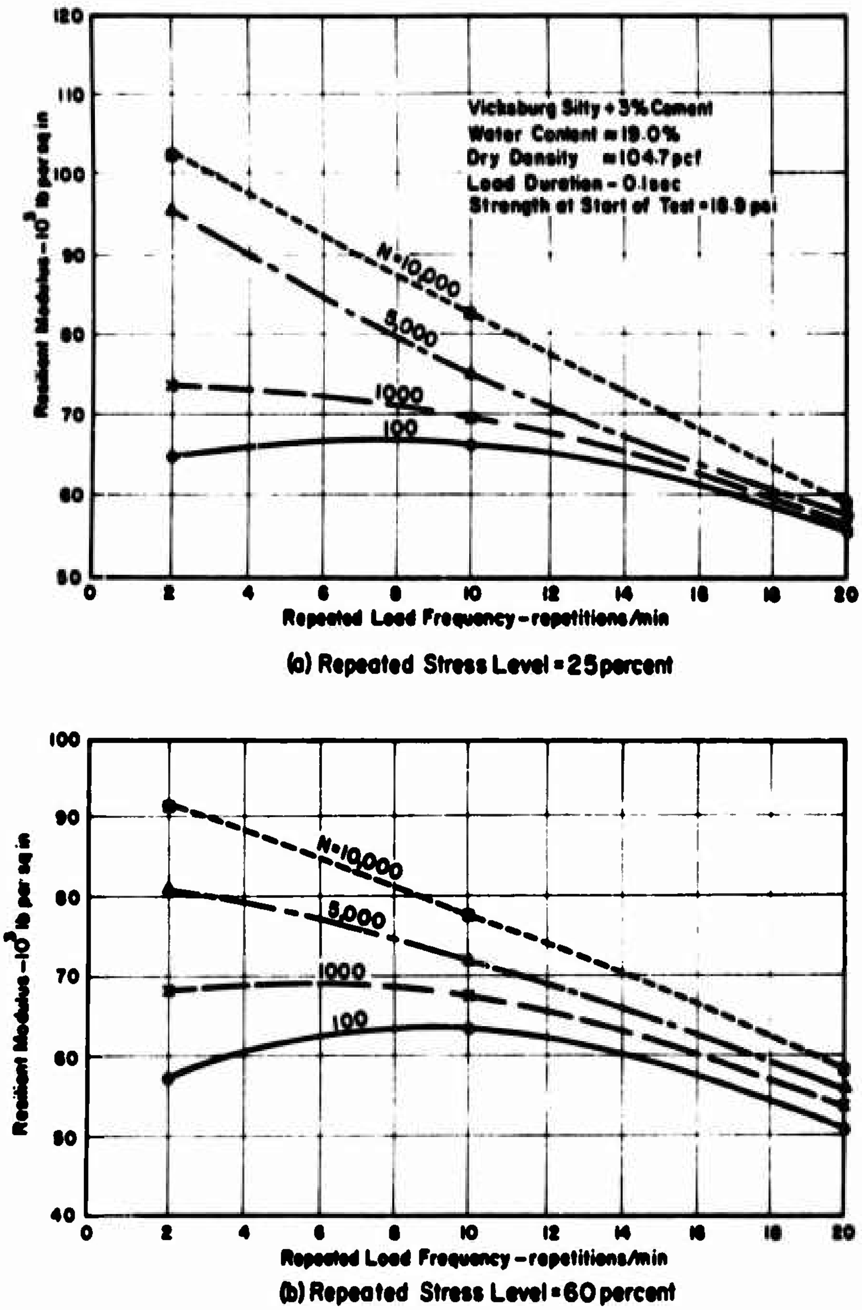


FIG. 37—RESILIENT MODULUS IN FLEXURE AS A FUNCTION OF FREQUENCY FOR DIFFERENT NUMBERS OF LOAD REPETITIONS.

25 and 60 percent. These curves show a progressive increase in modulus with decreasing frequency at large numbers of load repetitions. It appears that this increase results both from the increased curing period for strength development at the low frequencies and the tendency for the strength increase due to repeated loading to be greater for low frequencies (in the absence of fatigue failure). Evidence in support of this is shown by Fig. 38 which illustrates the effects of frequency on strength after repeated loading for several stress levels. In each case the sample had been subjected to 24,000 load repetitions. As may be seen the lower the frequency the greater the strength increase.

Insufficient tests were made to permit development of fatigue curves at each frequency. However, Fig. 39 indicates a range of stress levels within which flexural fatigue will develop within 24,000 load repetitions. Again the greater resistance of specimens subjected to low frequencies is evident. It should be pointed out, however, that direct extension of these results to field conditions could be misleading since the longer time required for a given number of repetitions at low frequencies provides greater opportunities for formation of temperature and shrinkage cracks.

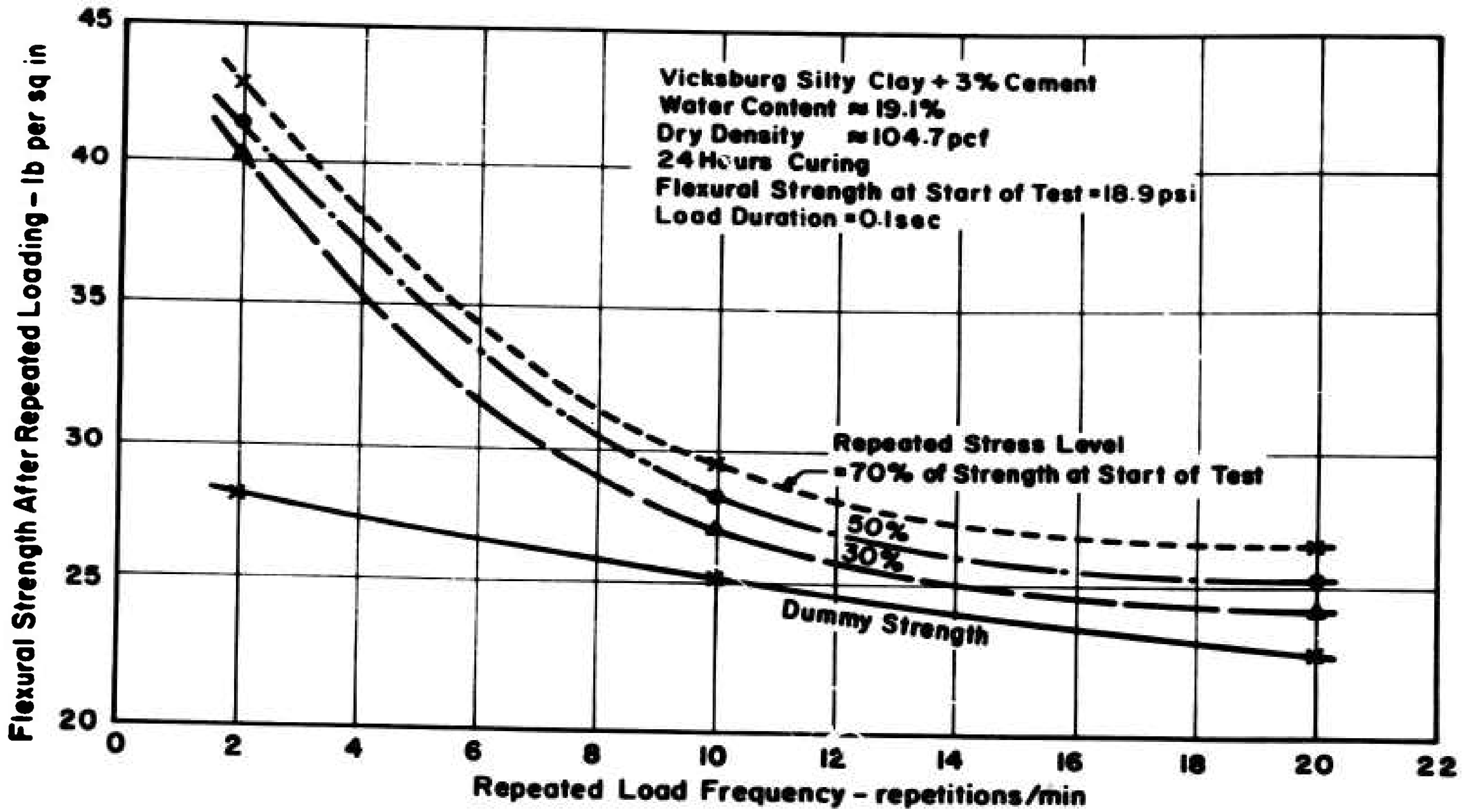


FIG. 38 — FLEXURAL STRENGTH AFTER REPEATED LOADING AS A FUNCTION OF FREQUENCY.

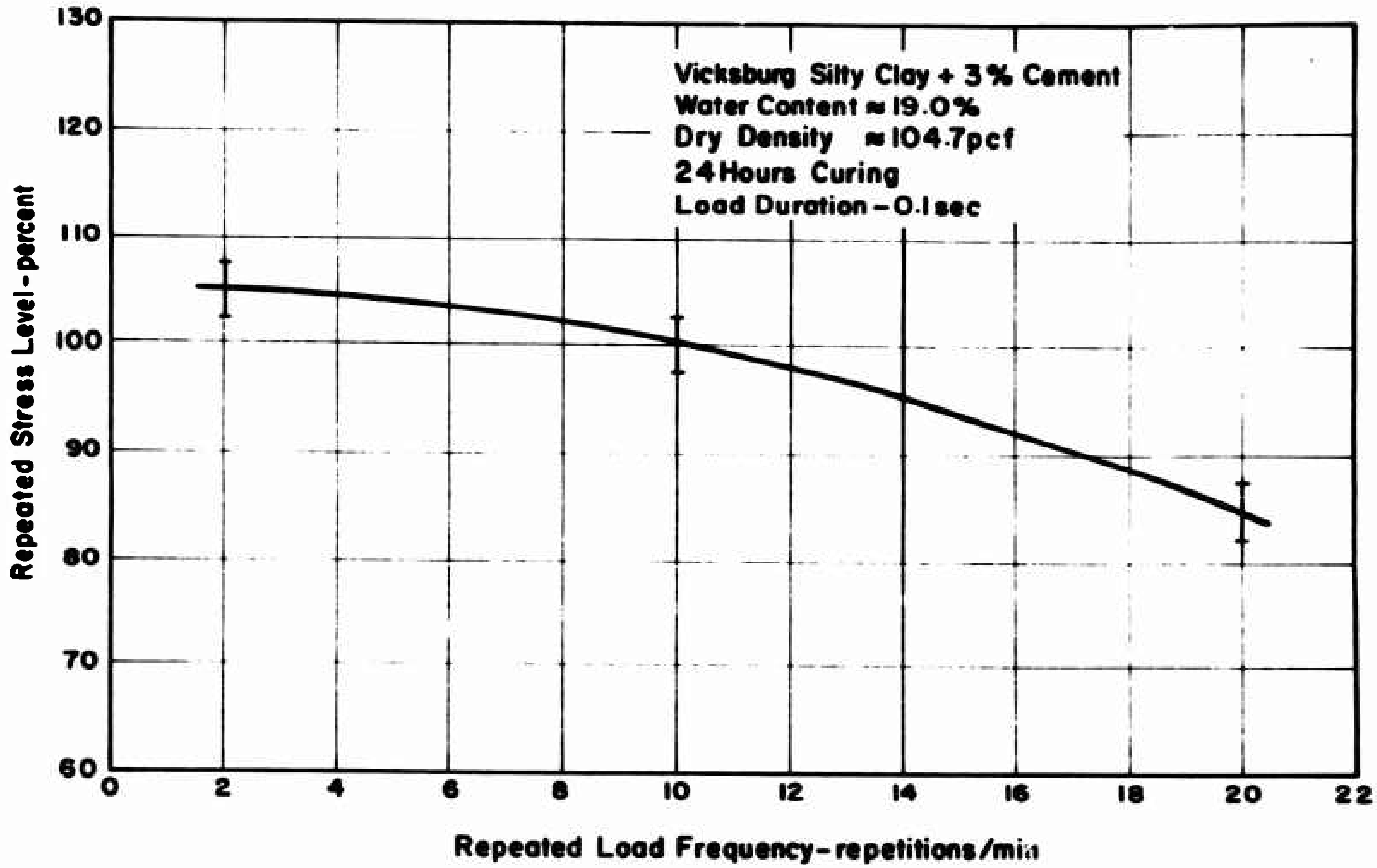


FIG.39— FLEXURAL STRESS LEVEL CAUSING FATIGUE FAILURE WITHIN 24,000 REPETITIONS AS A FUNCTION OF FREQUENCY.

V. REPEATED LOAD DURATION EFFECTS

Introduction

The duration of repeated loads due to traffic will depend primarily on the tire contact areas of the moving vehicles and their speeds. All test results reported thus far pertain to a load duration of 0.1 sec. For a tire having a 12 inch contact length this would correspond to a vehicle speed of about 7 mph. Shorter durations corresponding to higher vehicle speeds could not be readily studied because of apparatus limitations. Slower speeds than 7 mph are not unusual in some military situations, however, and the longer durations associated with these speeds might be expected to cause more destructive effects on the pavement. Consequently, the effects of load durations of 0.2 and 0.5 sec. have been investigated. These durations correspond approximately to vehicle speeds of 3-1/2 and 1-1/2 mph.

It is likely also that the stabilized soil will be required to support parked vehicles and aircraft, thus providing continuous loading. An investigation was therefore made of the deformations caused by a sustained loading of 24 hours duration. All tests were made using silty clay treated with 3 percent cement and cured for 24 hours. Specimens were compacted at a water content of 19 percent and to a dry density of 104.7 pcf.

Sustained Load Tests

Fig. 40 shows the relationship between initial strain and total and recoverable strain after sustained compressive loading of 24-hours duration. It may be noted that the recoverable strain is only a small part of the total strain and that the relationships between stress and strain are non-linear with increase in strain more than directly proportional to stress. These values may be compared with those for similar specimens subjected to repeated loading and presented in the next section.

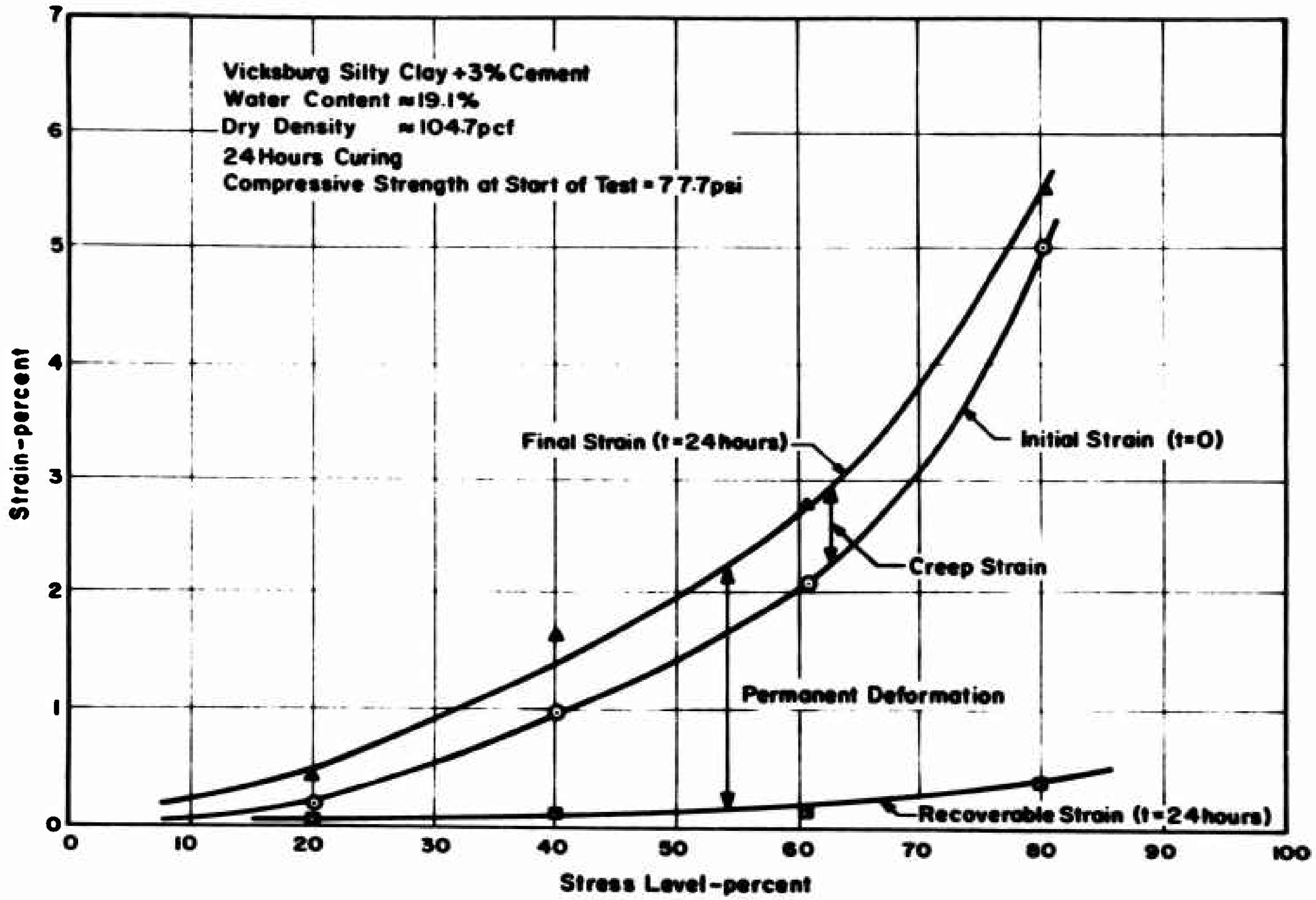


FIG.40—COMPRESSIVE STRAINS AS A FUNCTION OF STRESS LEVEL FOR SUSTAINED LOADING.

Effect of Duration on Behavior in Repeated Compression

All repeated load tests in the duration study were conducted at a frequency of 20 repetitions per minute. The effect of load duration in compression on the total strain during repeated loading did not appear significant. However, the results suggested the possibility that the total strain under load might be slightly less at a duration of 0.2 sec. than at either 0.1 or 0.5 sec. Whether this finding is real or a result of experimental error is not clear. If it is real the cause could perhaps be attributed to the fact that the repeated compressive loads tend to do two things: (1) break down the structure, a weakening effect, and (2) densify the structure, a strengthening effect. In such a situation it would be expected that a minimum strain condition might exist at some intermediate duration.

A comparison between the total strains after 24,000 load repetitions for different stress intensities and the total strain in identical specimens subjected to sustained loads for the same period of time is presented in Fig. 41. Since 24,000 load repetitions requires 20 hours, the sustained stress values represent total deformation after 20 hours in a creep test. It may be seen from Fig. 41 that the total compressive strains, although somewhat scattered, are not significantly different regardless of repeated load duration or whether the stress is maintained on the sample continuously. Since Seed, Chan and Monismith (1955) found that repeated load duration had a marked influence on strains in untreated Vicksburg Silty Clay, it would appear that the cement treatment has a marked influence on the deformation characteristics.

The resilient strains after 24,000 load repetitions of different durations are compared with the recoverable strains after creep tests in Fig. 42. The results suggest that the resilient strain after sustained loading is somewhat greater than that after repeated loading for the same time period. It was also found that the variation in resilient strain with duration of loading was small even though strains decreased progressively with increased numbers of repetitions. Fig. 43 shows this behavior for two repeated stress levels. These variations have some influence on

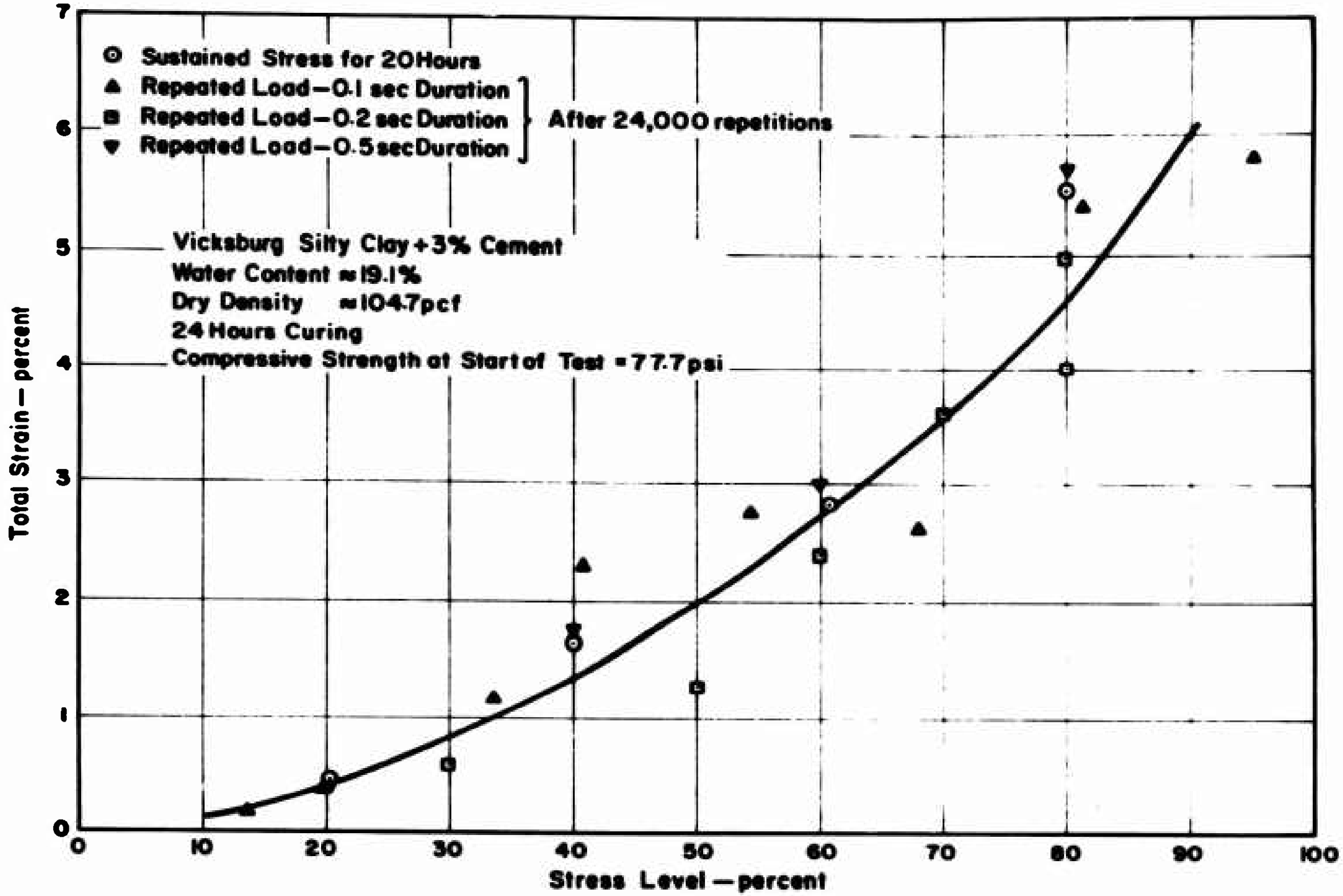


FIG. 41 — TOTAL COMPRESSIVE STRAIN AS A FUNCTION OF STRESS INTENSITY FOR DIFFERENT REPEATED LOAD DURATIONS.

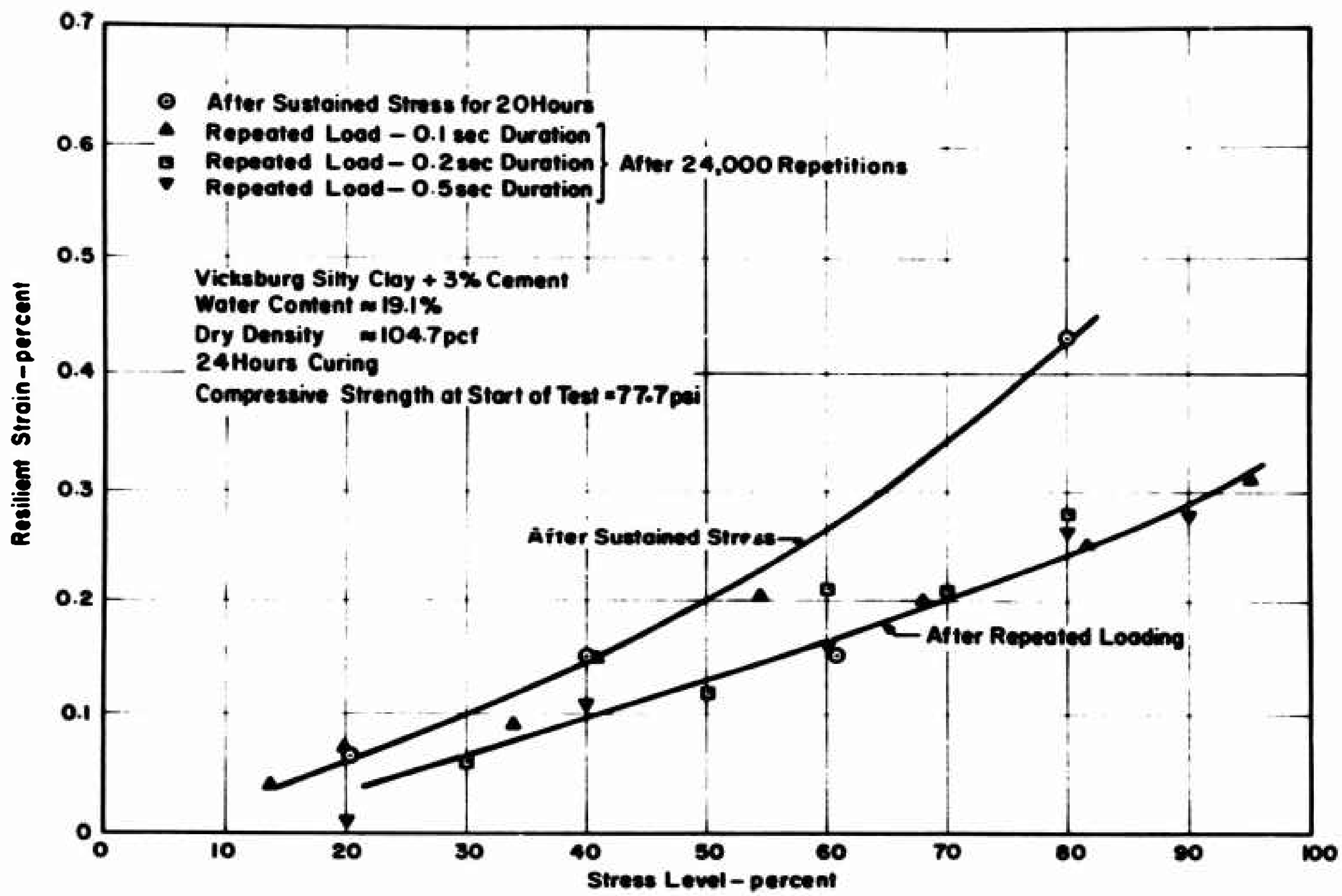


FIG. 42— RESILIENT COMPRESSIVE STRAIN AS A FUNCTION OF STRESS INTENSITY FOR DIFFERENT REPEATED LOAD DURATIONS.

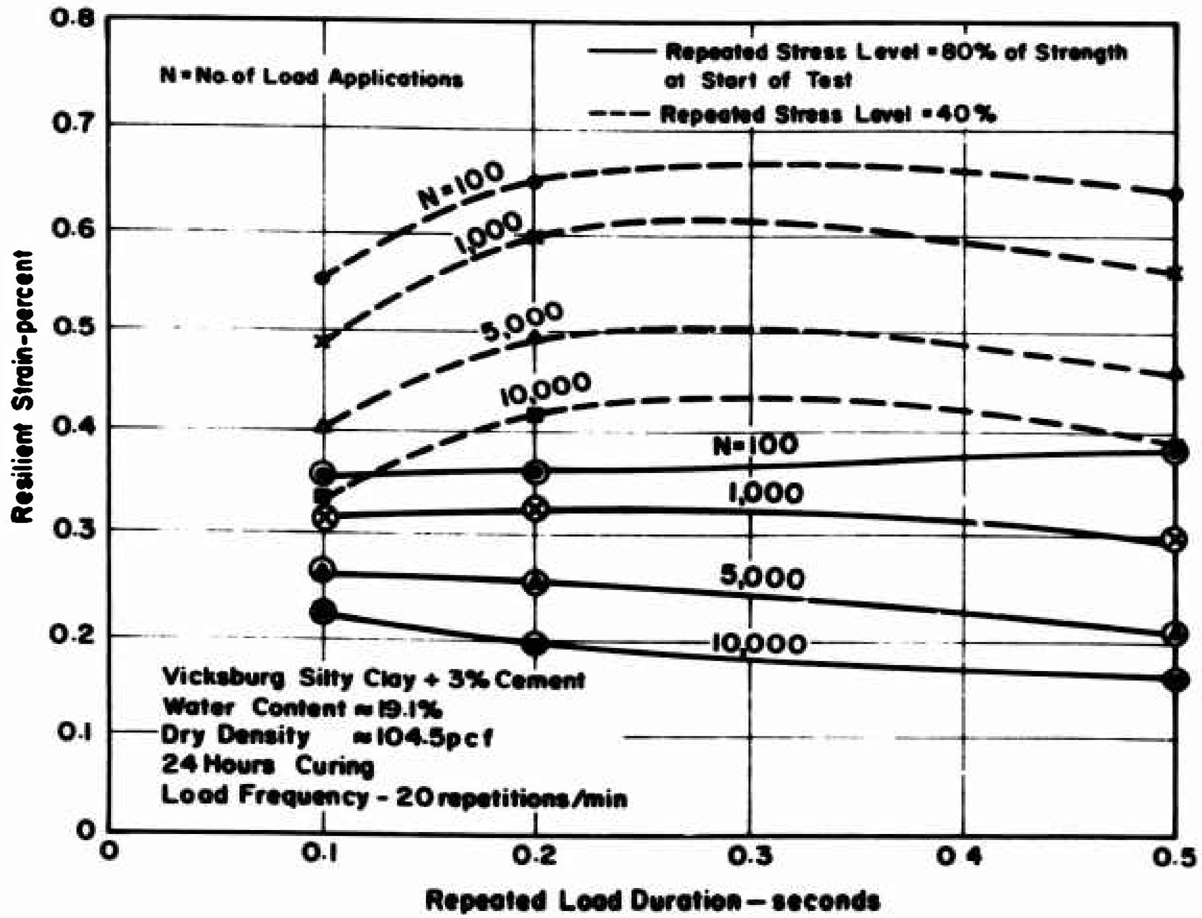


FIG.43— RESILIENT COMPRESSIVE STRAINS AS A FUNCTION OF REPEATED LOAD DURATION.

the resilient modulus as shown in Fig. 44; however, the effect of duration on modulus for stress levels greater than 50 percent is minor. Thus the effects of load duration variation on behavior are seen to be minor in comparison to those caused by frequency variation.

Similarly it was found that the duration had only minor effects on properties after repeated loading. Fig. 45 shows that the compressive strength after repeated loading was slightly greater for a duration 0.1 sec. than for durations of 0.2 and 0.5 sec. Strains at failure were not influenced by duration of repeated loads. The results did show, however, that specimens could withstand greater stress intensities without failure with decreasing load duration. Fig. 46 illustrates this effect in terms of the approximate stress level required to cause fatigue failure in compression within 24,000 load repetitions.

Effect of Duration on Behavior in Repeated Flexure

The effects of repeated load duration on behavior in repeated flexure were studied over a duration range of 0.1 to 0.5 seconds for a stress level of 50 percent of the initial strength. Fig. 47 shows that the load duration had essentially no affect on the total strains after any given number of load repetitions. On the other hand, Fig. 48 shows that at the shortest duration (0.1 sec.) the permanent tensile strain is smaller and the resilient strain is greater than at the longer durations. This behavior may reflect the fact that the development of permanent plastic strain is time dependent. At the shortest duration insufficient time may be available for this deformation to occur.

As a consequence of the larger resilient deformations at short load duration the resilient modulus is least at the shortest duration as shown by Fig. 49. Reference to Fig. 44 shows that at low stress levels similar behavior was observed for repeated loading in compression. Intuitively it would be expected that loads of short duration would be less damaging to a pavement structure. Considerable evidence is available to show that fatigue of pavement components is related to the magnitude of resilient strains. Thus it may be that under some circumstances short duration

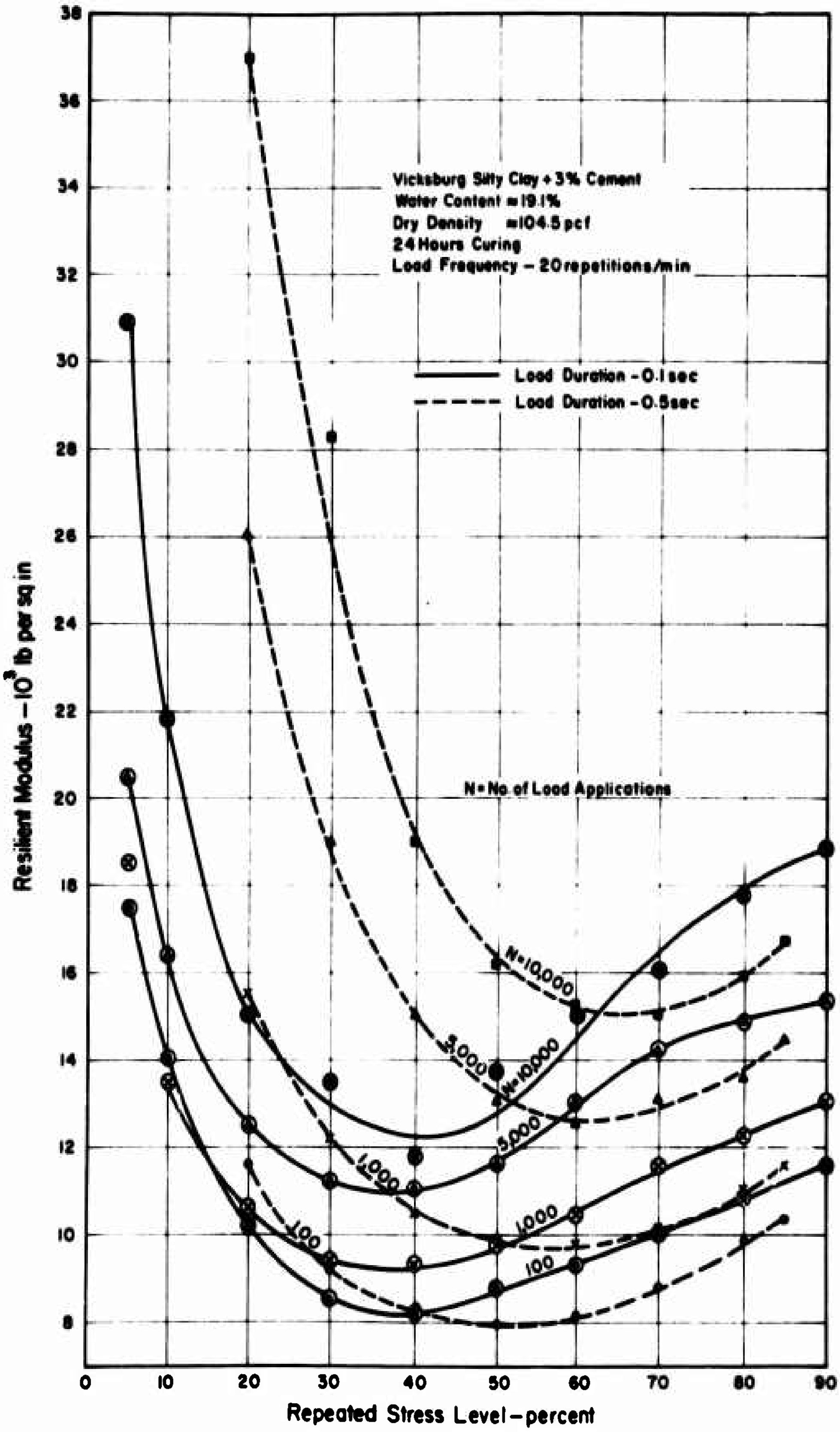


FIG.44 – INFLUENCE OF REPEATED LOAD DURATION OF RESILIENT MODULUS IN COMPRESSION.

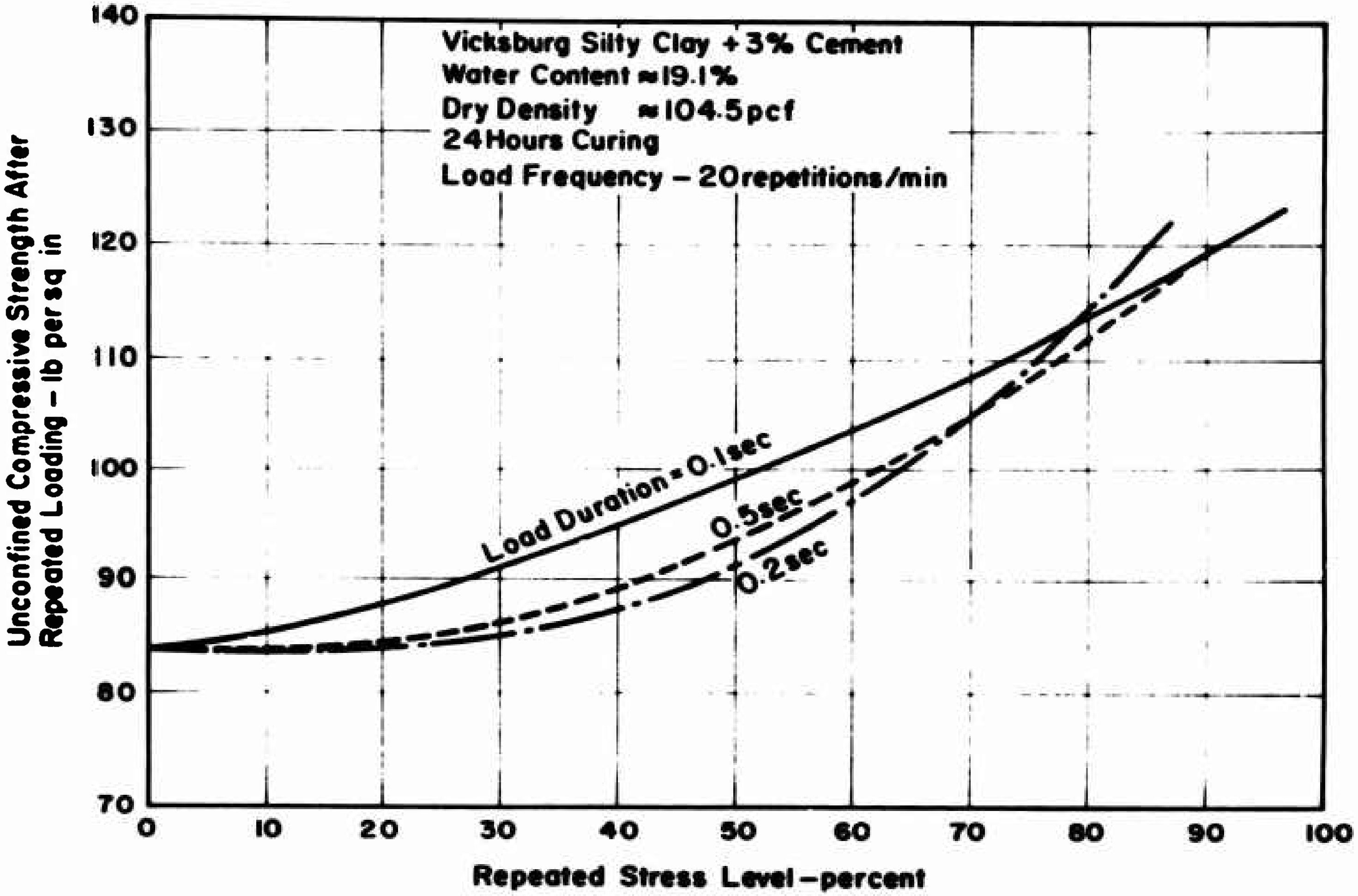


FIG. 45 – COMPRESSIVE STRENGTH AFTER REPEATED LOADING AS AFFECTED BY REPEATED LOAD DURATION.

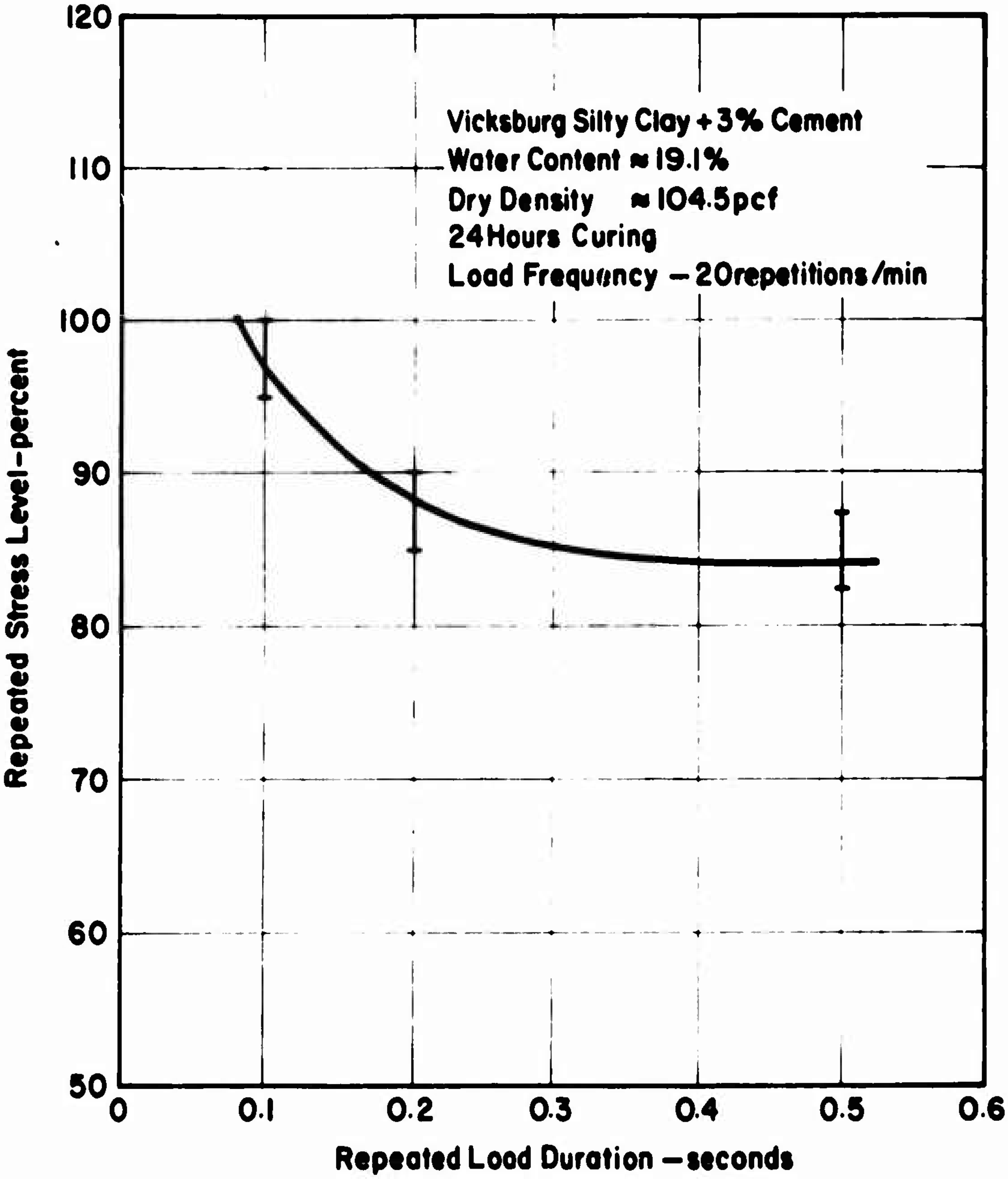


FIG.46 — EFFECT OF REPEATED LOAD DURATION ON STRESS LEVEL REQUIRED TO CAUSE FATIGUE FAILURE WITHIN 24,000 REPETITIONS IN COMPRESSION.

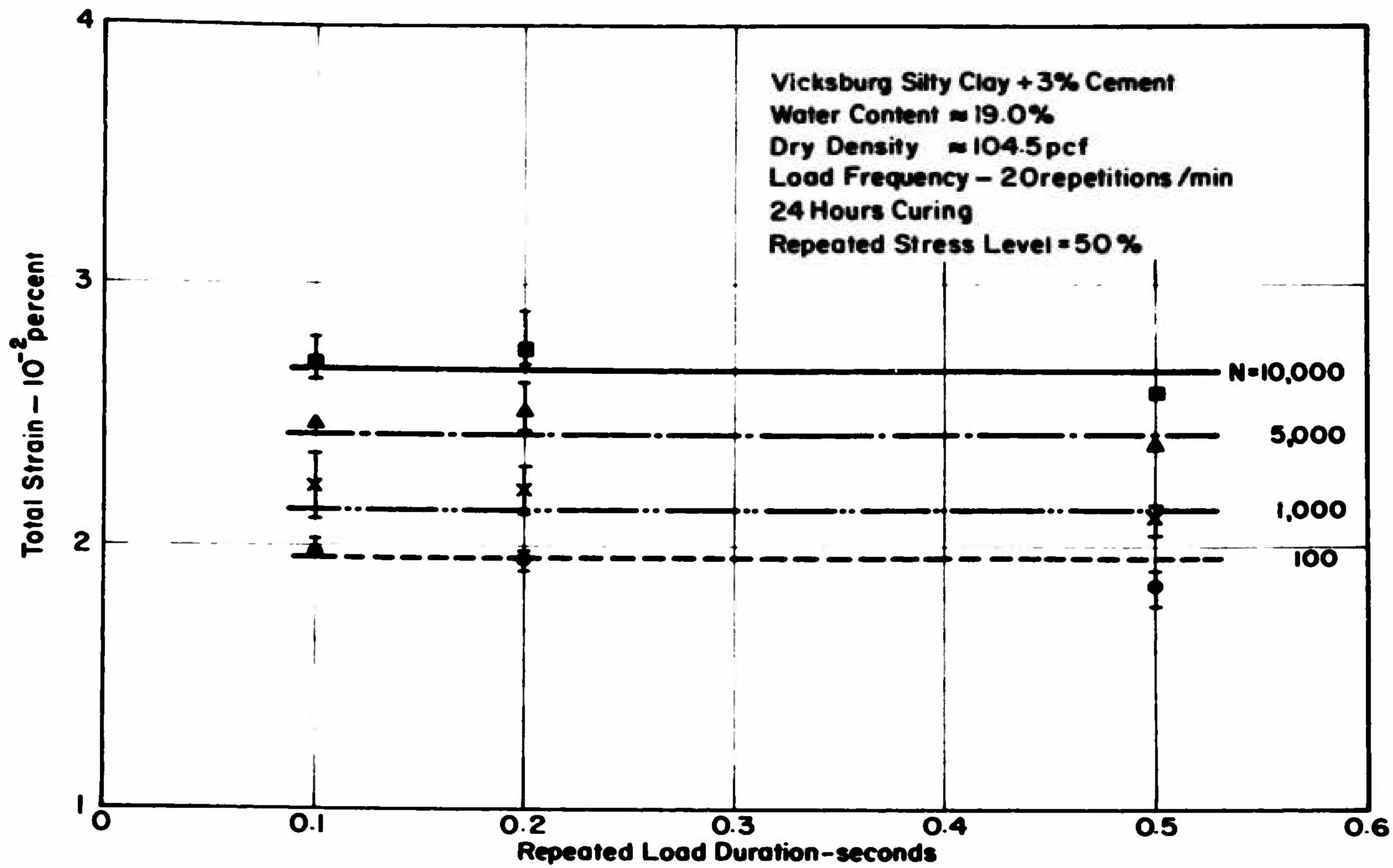


FIG.47— TOTAL FLEXURAL STRAIN AS A FUNCTION OF REPEATED LOAD DURATION.

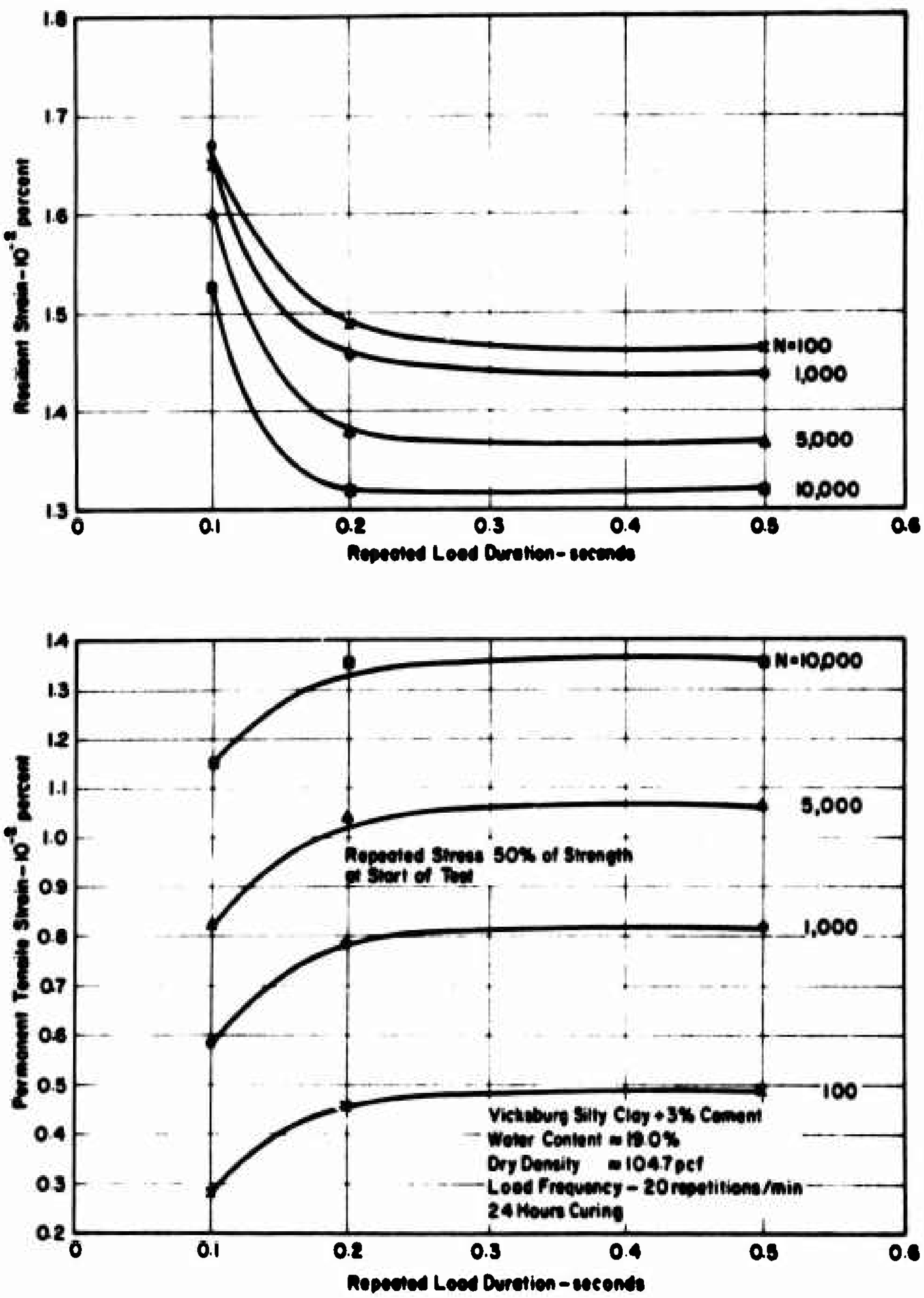


FIG. 48 — EFFECT OF LOAD DURATION ON RESILIENT AND PERMANENT STRAINS IN FLEXURE.

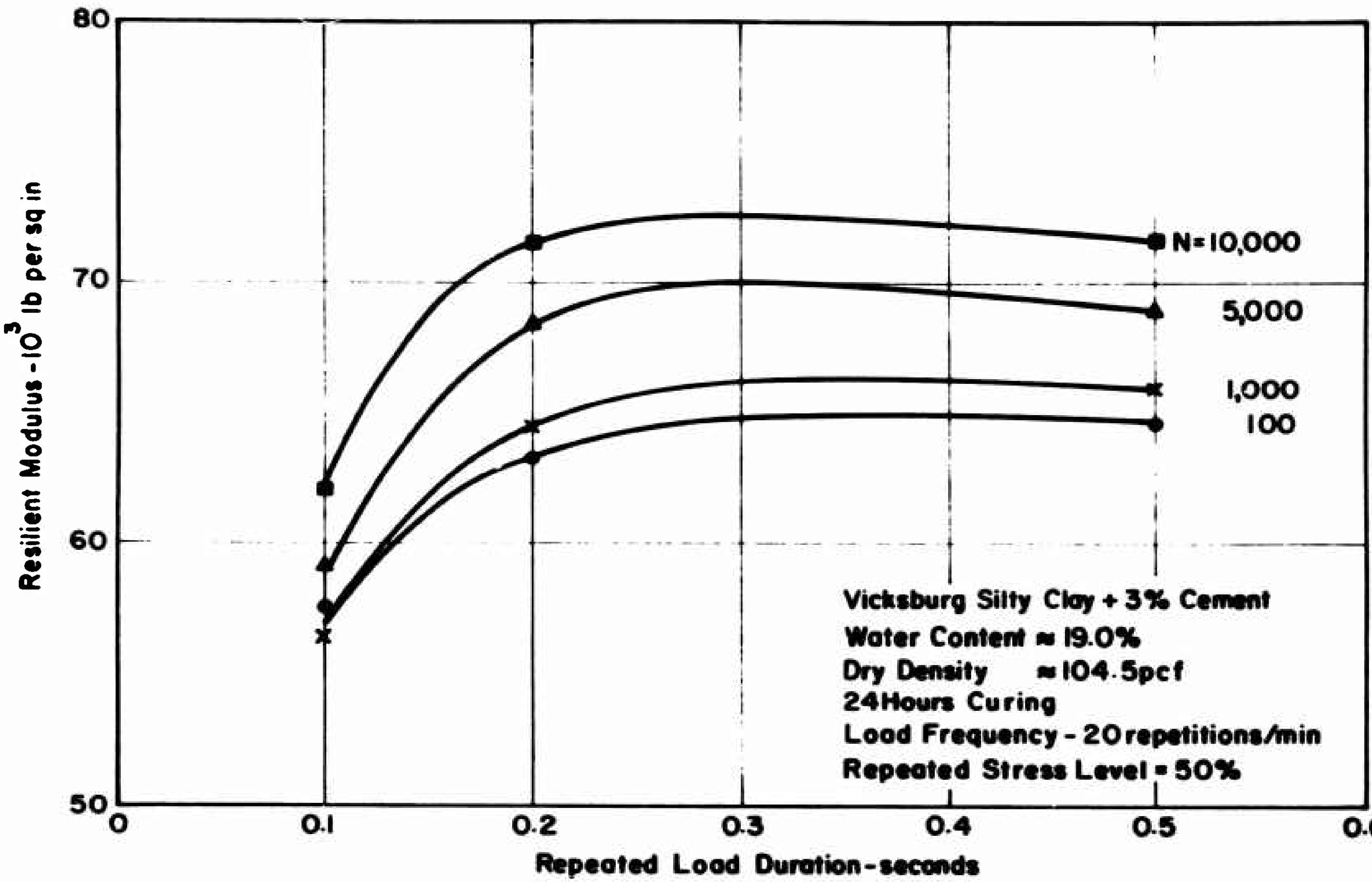


FIG.49—EFFECT OF LOAD DURATION ON RESILIENT MODULUS IN FLEXURE.

loads may be more damaging than long duration loads. Considerably more information is needed to substantiate this possibility, however.

Repeated loading in flexure led to some increase in strength after 24,000 load repetitions. This increase was somewhat greater for durations of 0.1 and 0.2 sec. than for a duration of 0.5 sec. More data are needed however, to better establish the significance and magnitude of this effect.

VI. ANALYSIS OF PROBABLE PAVEMENT PERFORMANCE

Introduction

On the basis of the property values reported in the preceding sections and in Report 1 it is possible to investigate the probable performance of stabilized sections under the prescribed loadings for roads and airfields in the theater of operations. This analysis may be made based on stresses predicted using layered system elastic theory and comparing the stresses so deduced with the known strength and fatigue characteristics.

For the analyses reported herein moduli values for the stabilized layer and subgrade were assumed to be related to the CBR according to (Peattie, 1962).

$$E = 1560 \text{ CBR (in psi)}.$$

Thus for a subgrade with a CBR of 4 the modulus would be about 6250 psi, and for a layer stabilized to a CBR of 20 it would be about 30,000 psi. The test results reported herein show that these values are reasonable approximations for the cement-treated silty clay, but that more exact analyses should take account of several additional factors. Some of these are:

1. The resilient modulus varies with stress intensity, load duration and frequency, number of load repetitions, and curing period.
2. Resilient moduli in compression may be significantly less than 30,000 psi, as shown for example by Fig. 27, Report 1, and Figs. 30 and 44 of this report. The modulus may be as low as 5000 psi under some conditions when the material still satisfies the CBR criteria.
3. Resilient moduli in flexure may be significantly greater than 30,000 psi, as shown for example by Fig. 49. Under some conditions it may exceed 70,000 psi.

Thus precise evaluation of stresses and deflections for any given pavement section will require an iterative analysis of thicknesses, moduli and stresses until compatability is attained. At present, however,

the simple correlation between CBR and modulus given above would appear to represent adequately average values which are sufficient for investigating the probability of cracking and failure in pavements constructed according to the Corps criteria.

Tensile Stresses in Stabilized Layers

In Report No. 1, elastic theory for layered systems was used to derive a relationship between tensile stress at the base of a stabilized layer and layer thickness for a simplified representation of the gear configuration for a C-124 aircraft. Results were shown for a range in moduli (or CBR's) for the stabilized layer, and indicated that the tensile stress at the underside of the stabilized layer was significantly affected by layer thickness but was virtually independent of the strength of the stabilized layer. Unfortunately the information used in developing this figure was erroneously interpreted. A correct analysis is presented in Fig. 50.

In this figure it will be noted that much larger values for tensile stress are obtained than shown earlier and that the tensile stresses, as well as being influenced by layer thickness, are markedly affected by the CBR (modulus) of the treated layer.

Also in Report No. 1 it was indicated that the C-124 aircraft appeared to produce the most critical loading conditions as far as stress on the underside of the treated layers are concerned. This is substantiated by the data presented in Fig. 51. In this figure tensile stress vs layer thickness data are presented utilizing simplified representations of two additional aircraft gear configurations and a cargo truck considered critical according to the Corps criteria. These curves as well as that for the C-124 were developed using the following assumptions:

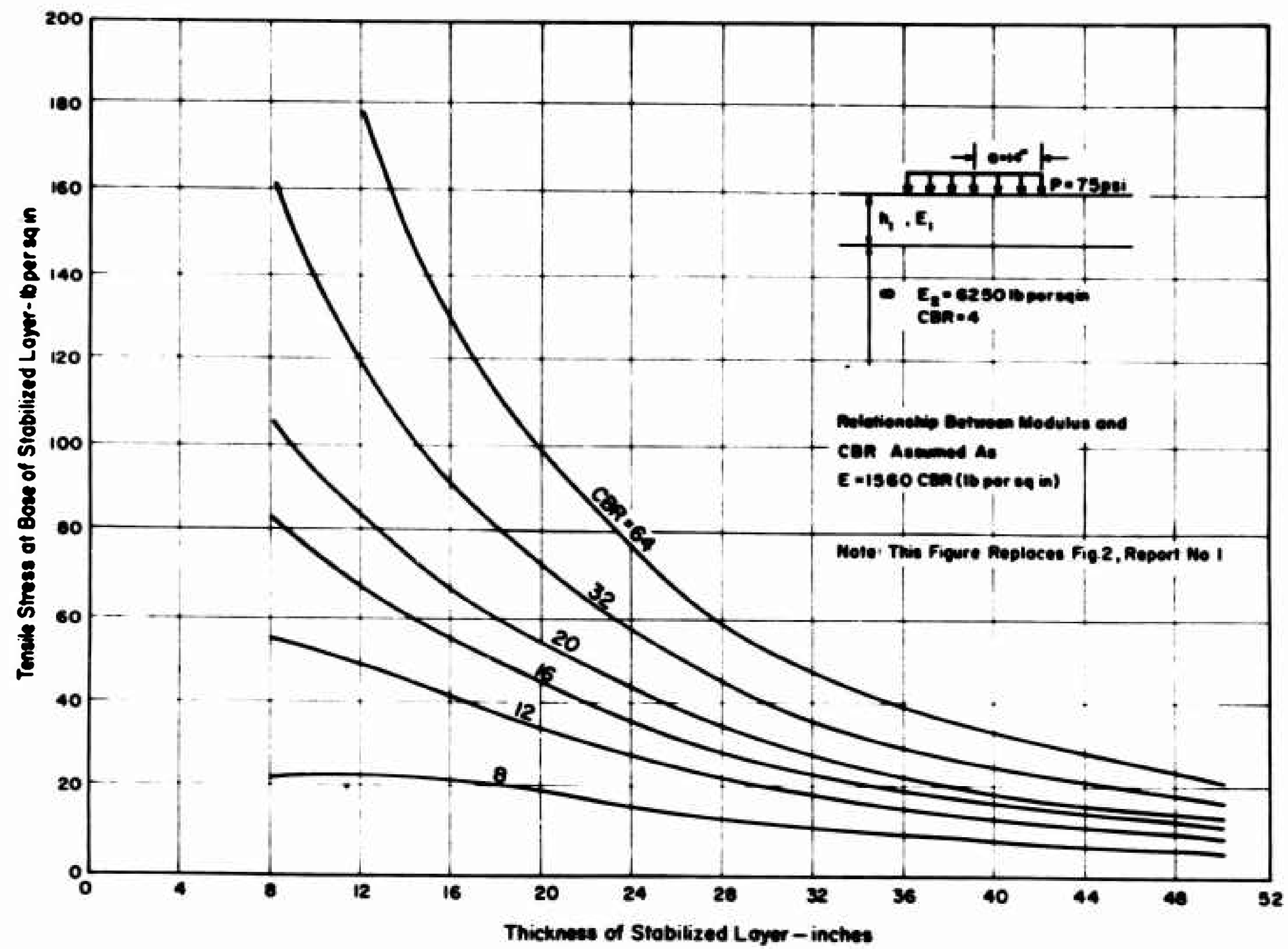


FIG.50 – TENSILE STRESS AT THE UNDERSIDE OF THE STABILIZED LAYER AS A FUNCTION OF LAYER CBR AND THICKNESS FOR C-124 AIRCRAFT LOADING.

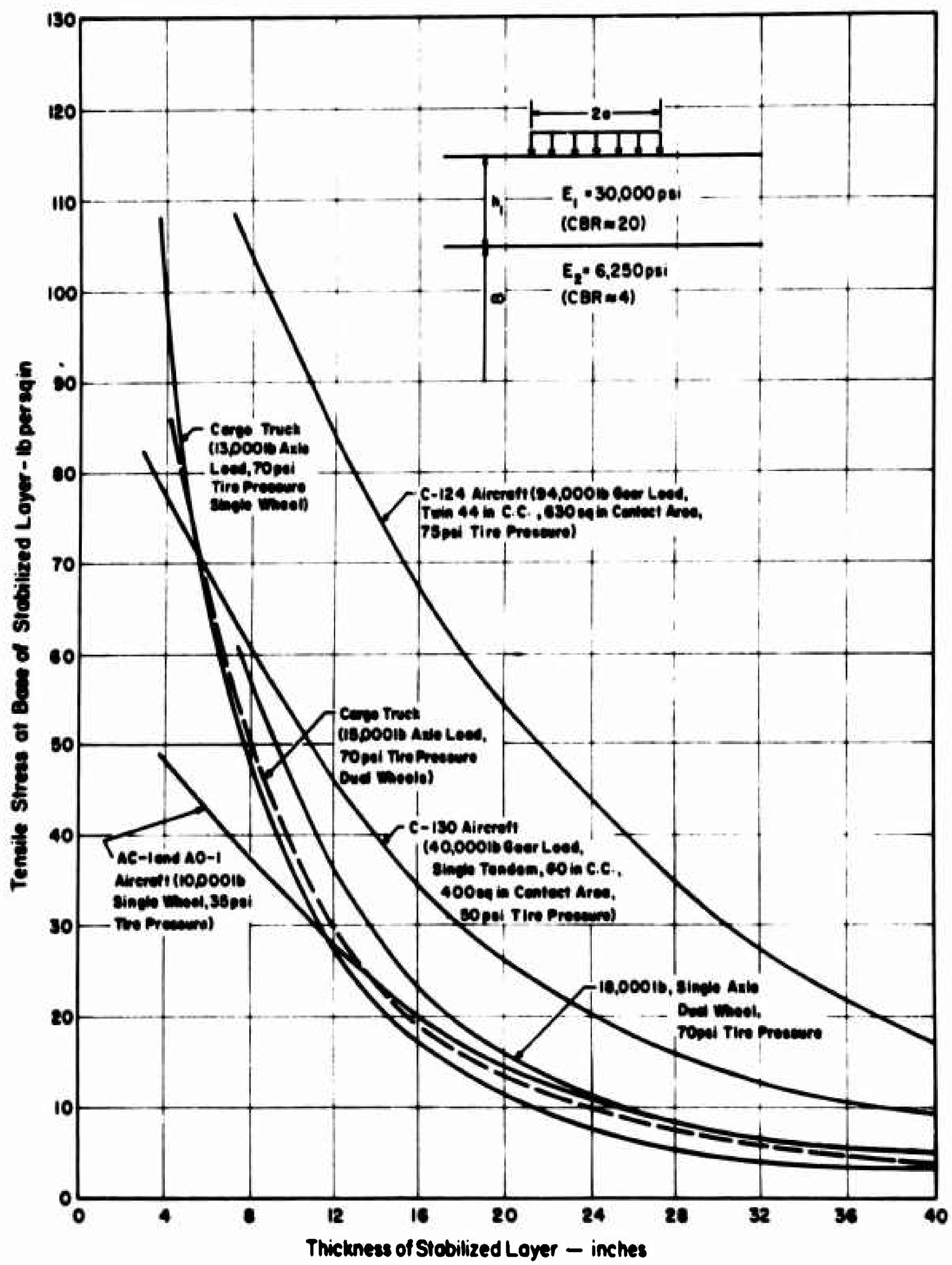


FIG. 51— TENSILE STRESSES AT BASE OF STABILIZED SOIL LAYER (CBR = 20) AS A FUNCTION OF LAYER THICKNESS.

Aircraft or Vehicle	Wheel load - lb	Contact Pressure psi	Contact Area - in^2	Radius of Loaded Area, a in.
C124	47,000	75	630	14.0
C130	20,000	50	400	11.3
AC-1, AO-1	10,000	35	286	9.55
Cargo Truck	6,500	70	92.8	5.45
Cargo Truck	7,500	70	107	5.85
Cargo Truck	9,000	70	128.5	6.40

The curves of Fig. 51 together with the flexural fatigue curve presented in Fig. 14 can be used to estimate the required thicknesses to prevent fatigue cracking for the various classes of roads and airfields in the theater of operations. The following table summarizes these results.

Pavement	Applicable Curve Figure 51	No. of Coverages	Allowable Flexural Stress From Fig. 14 psi	Computed Thickness to Prevent Fatigue Cracking, in.	Thickness Corps of Engineers Criteria**
Airfield Class 1-A	AC-1 and AO-1	40	15.7	16.5	--
Airfield Class 2-A	C-130	200	14.2	30.0	9
Airfield Class 3-A	C-124	200	14.2	42	22
Road Class 1-R	Cargo truck, 18,000 lb.	44	15.5	20*	10
Road Class 2-R	Cargo truck, 18,000 lb.	1300	13.2	22*	12

*Based on equivalent number of passes of 18,000 lb. axle load (Table 1, Report No. 1 presents the basis for use of the 18,000 lb. equivalent wheel load for loading conditions on class 1-R and 2-R roads).

**Table 3, Report 1.

For all cases the computed thicknesses are substantially larger than the maximum thicknesses indicated by the Corps of Engineers criteria (Table 3, Report 1). This analysis, however may give very conservative results, and, as indicated in the first part of

this section, an iterative trial and error procedure is probably required to obtain a realistic estimate of thickness.

In this analysis, for example, a constant modulus was assumed for the subgrade in computing the required thicknesses. As the thickness of the stabilized layer is increased the stress on the subgrade will be reduced and as indicated in Fig. 1, Report No. 1, the modulus of the subgrade is increased. This type of behavior may also be applicable to the silty clay utilized in this investigation. While no tests were performed on the untreated soil, data were obtained in another investigation illustrating such effects. These data are presented in Fig. 52.

For the larger thicknesses, the stress at the interface between the stabilized layer and the subgrade will be in the range where a small change in stress results in a significant increase in modulus. Correspondingly the modular ratio of the stabilized layer to that of the subgrade will be reduced. This reduction, in turn, will result in smaller tensile stresses in the stabilized layer. Consequently the curves of stress vs. thickness shown in Fig. 51 in all probability give very conservative tensile stresses in the higher thickness range due to this aspect of behavior.

Another factor to be considered, which acts in the opposing direction, is the increase in flexural stiffness with time. In the above analysis, the flexural stiffness of the stabilized layer obtained at 24 hours curing was used in the analysis. This value is smaller than that which might be obtained for larger periods of time in the case of the Class 2-R road and Class 2-A and 3-A airfields. Thus even though the modulus of the subgrade is increased with increase in layer thickness the modular ratio may be higher thus resulting in larger tensile stresses.

In addition, a flexural strength obtained after 24 hours cure was also used as the basis for the analysis. As seen in Fig. 10 this value may also be conservative.

Thus it can be seen that a number of factors in addition to those listed on page 84 complicate an analysis such as that presented above and

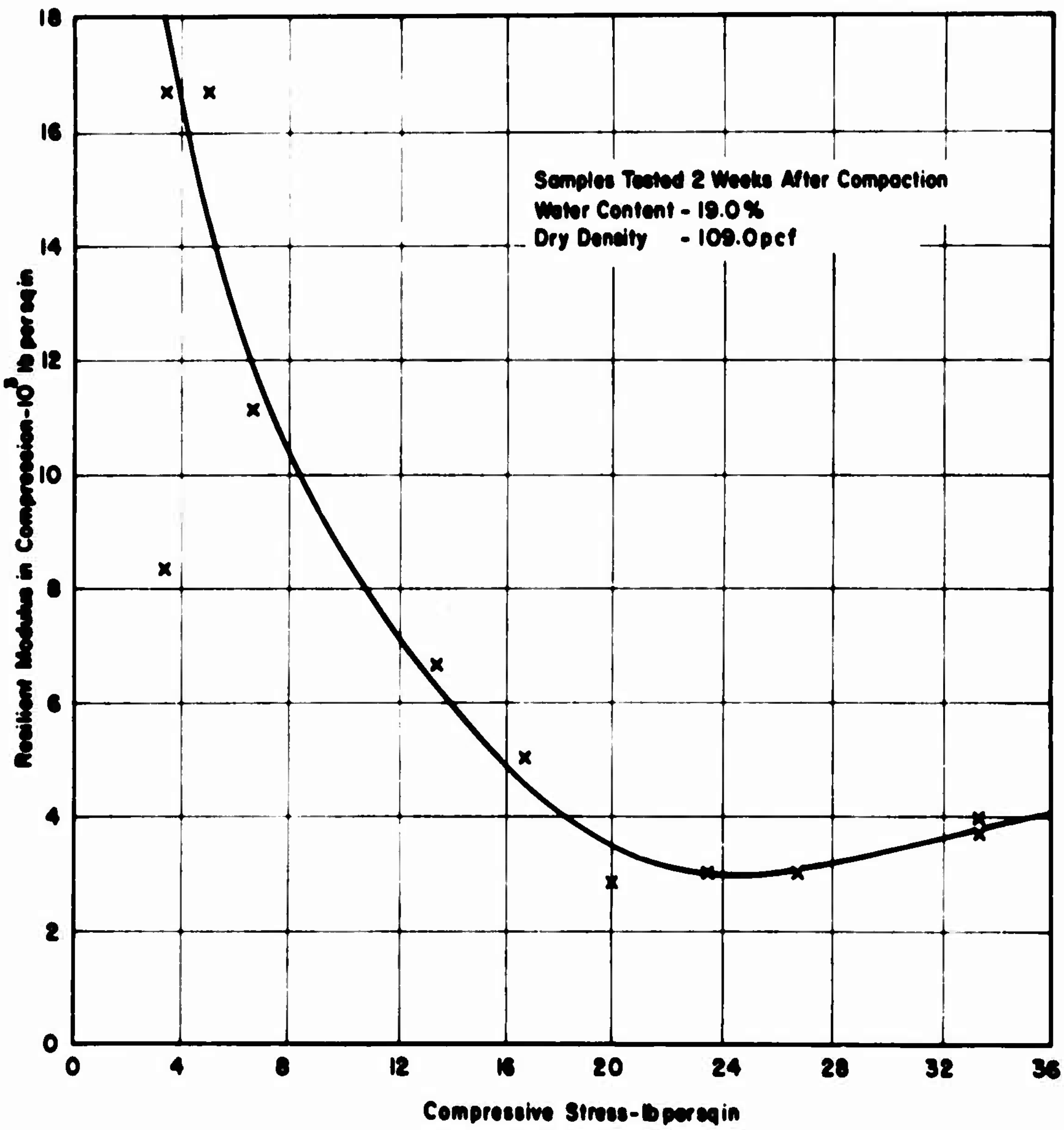


FIG.52—RESILIENT MODULUS IN COMPRESSION AS A FUNCTION OF STRESS INTENSITY FOR UNTREATED VICKSBURG SILTY CLAY.

it is possible that the computed thicknesses shown on page 88 are conservative. Furthermore the results of the analysis suggest only that sections stabilized to satisfy Corps criteria for strength and thickness will crack under the imposed loads. It is entirely possible that the sections could withstand the design traffic in the cracked condition, performing in much the same manner as a conventional pavement containing a granular base. It is planned to examine these considerations in more detail during the coming year both theoretically and with the aid of a small field test section.

Fatigue Failure Probability in Relation to Stabilization Variables

As already clearly indicated a large number of variables may influence the performance of a stabilized section under a specified loading. Among the more important of these are:

1. Initial water content of untreated soil
2. Stabilizer treatment level
3. Curing period prior to loading
4. Thickness of stabilized layer
5. Stress intensity
6. Load frequency
7. Load duration
8. Field environmental factors

A thorough investigation of the combined effects of all of these factors would be a formidable task. A method of analysis has been developed, however, which enables estimation of limiting conditions in terms of water content, stabilizer treatment level, curing period and pavement thickness at which a section may be expected to carry the coverages specified by the Corps criteria without developing fatigue cracking. This method of analysis draws on the experimentally determined relationships presented herein and in Report 1 and layered system elastic theory. This procedure can be best illustrated by means of an example.

It has been established that Vicksburg silty clay at a water content of 19 percent has a CBR of 4 and treatment with 3 percent cement results

in a CBR of 20 after a curing period of 24 hours. To investigate the effects of variations of these parameters on fatigue each has been varied separately with the others held constant.

Loading has been assumed to be that caused by an 18,000 lb single axle, dual wheel with 70 psi tire pressure. A design thickness of 22 inches has been chosen. Fig. 53 shows that for a subgrade CBR of 4 and a stabilized layer CBR of 20 the tensile stress at the bottom of the layer should be 13.3 psi.

Use was made of the following experimentally determined relationships and assumptions:

1. The relationship between unconfined compressive strength and CBR given in Report 1 and reproduced in Fig. 54.
2. The flexural fatigue curve for cement-treated silty clay given in Fig. 14. It is assumed that this relationship is valid for cement contents, curing times, frequencies and durations other than those for which it was determined as well. There is no doubt that this assumption introduces some error. Probably a different fatigue curve holds for each condition. Should a refined analysis be required separate curves could be obtained for each important condition. The extensive testing program needed to accomplish this does not appear justified for the approximate analysis herein, however.
3. Fatigue curves for water contents other than 19 percent can be approximated from the curve in Fig. 19 if needed. Fig. 14 shows that the stress level causing failure at 200 repetitions is of the order of 10 percent greater than at 24,000 repetitions. Thus estimates for 200 repetitions or other intermediate values can be made from Fig. 19.
4. One repetition in the repeated loading test is the equivalent of one coverage in the field.
5. The large difference in time for application of the full number of repetitions in the laboratory and in the field has no effect. This assumption is probably conservative in view of the greater curing period available in the field.

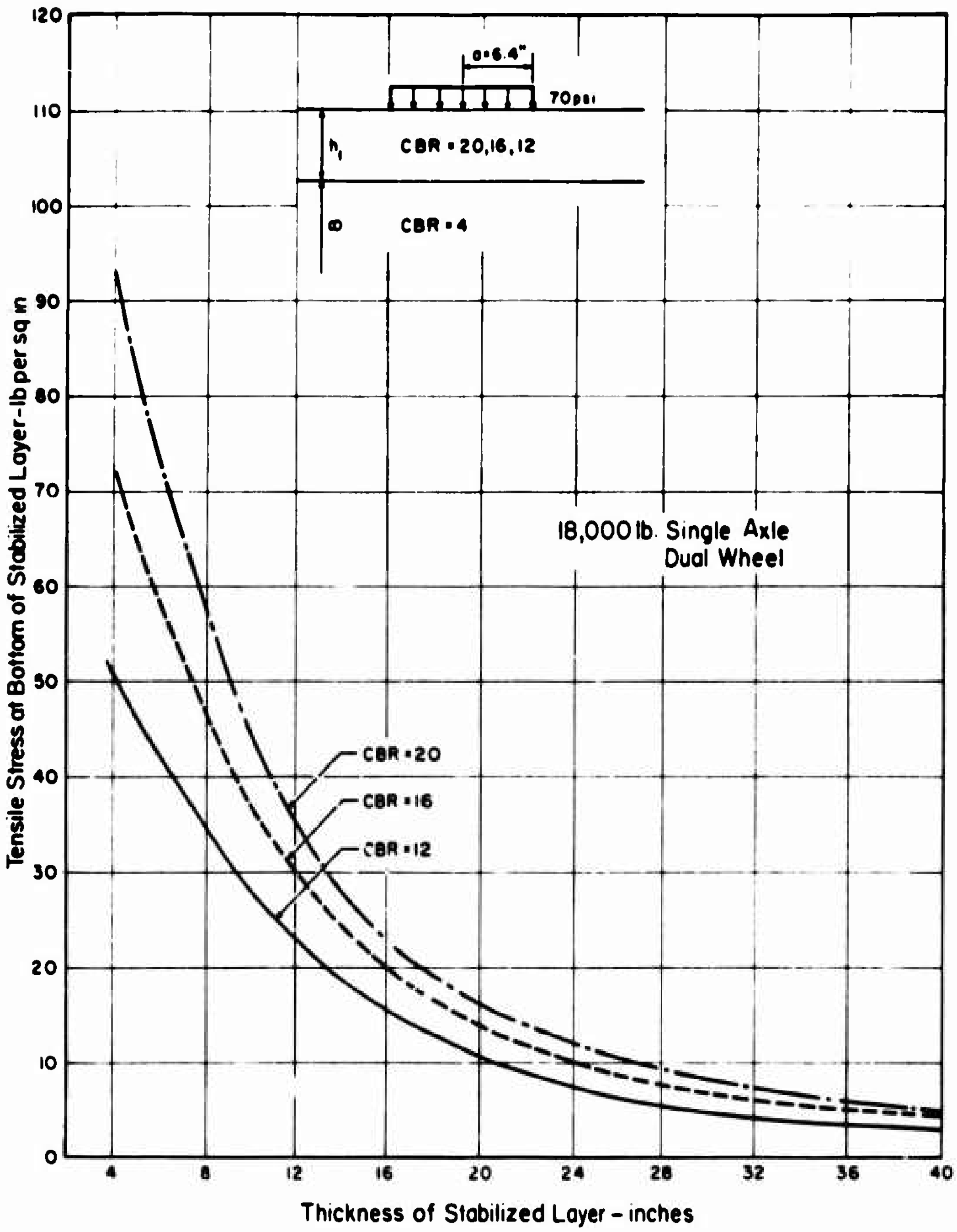


FIG.53 - TENSILE STRESSES AT BASE OF STABILIZED SOIL LAYER AS A FUNCTION OF LAYER THICKNESS FOR AN 18,000 lb SINGLE AXLE LOAD.

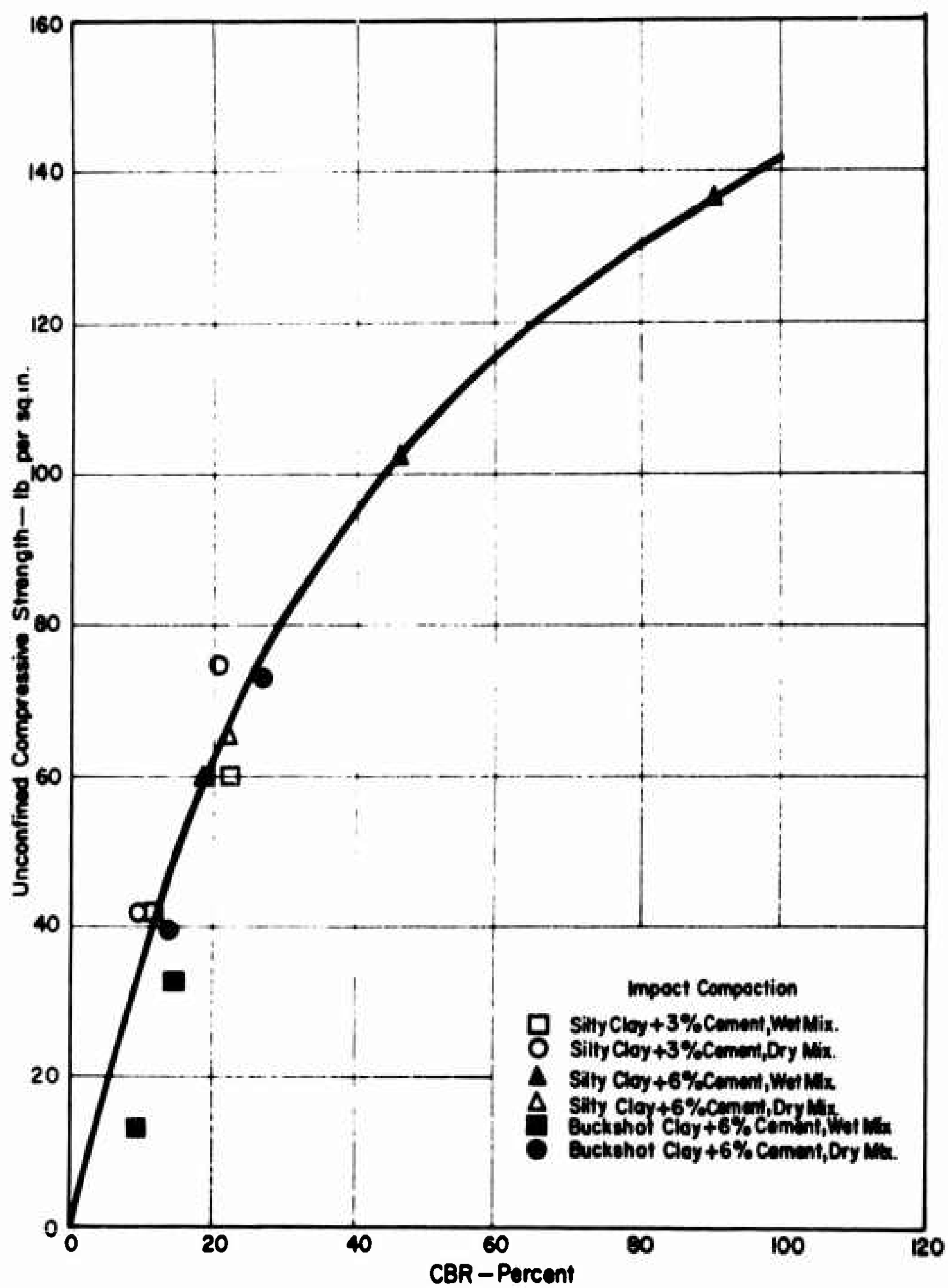


FIG. 54 — RELATIONSHIP BETWEEN UNCONFINED COMPRESSIVE STRENGTH AND CBR.

6. The variation in flexural strength with curing time is as given in Fig. 10.
7. The variation in flexural strength after 24 hours curing with cement content is as given in Fig. 55.
8. The variation in compressive strength with curing time is as shown in Fig. 56.
9. The variation in compressive strength after 24 hours curing with cement content is as given in Fig. 57.
10. The variation in flexural strength with water content is as shown in Fig. 9.
11. The variation in compressive strength with water content is as shown in Fig. 58.

12. The relationship between tensile stress at the base of the stabilized layer and layer thickness can be determined from two layer elastic theory. The relationship for a subgrade CBR of 4 and loading from the 18,000 lb single axle load is given in Fig. 53 for three values of CBR for the stabilized layer.

The analysis for variations in cement content, curing time, water content, and layer thickness is given in Table 1. Values in this table were obtained as follows:

1. Column (1) indicates the variable under study. The first two lines of the table indicated after "None" refer to values holding for the reference conditions of an initial water content of 19 percent, a cement content of 3 percent, a 24 hour curing period, a 22 inch thick stabilized layer, and loading from a 18,000 lb single axle load.
2. Column (2) gives the variable under study.
3. Column (3) indicates the unconfined compressive strength obtained from Fig. 56, 57, or 58, whichever is applicable.
4. Column (4) is obtained using the unconfined compressive strength in conjunction with Fig. 54.

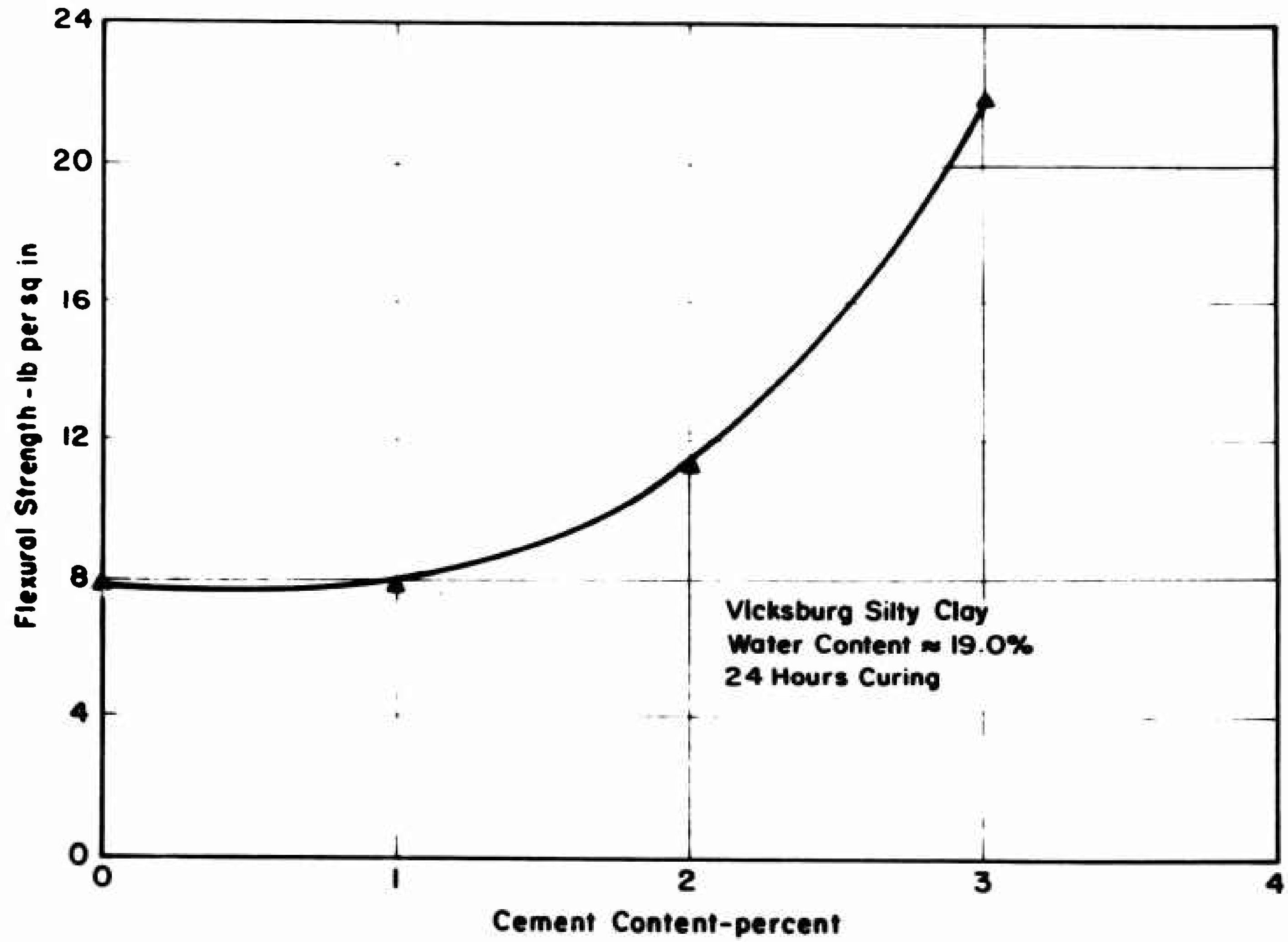


FIG.55—FLEXURAL STRENGTH AS A FUNCTION OF CEMENT CONTENT.

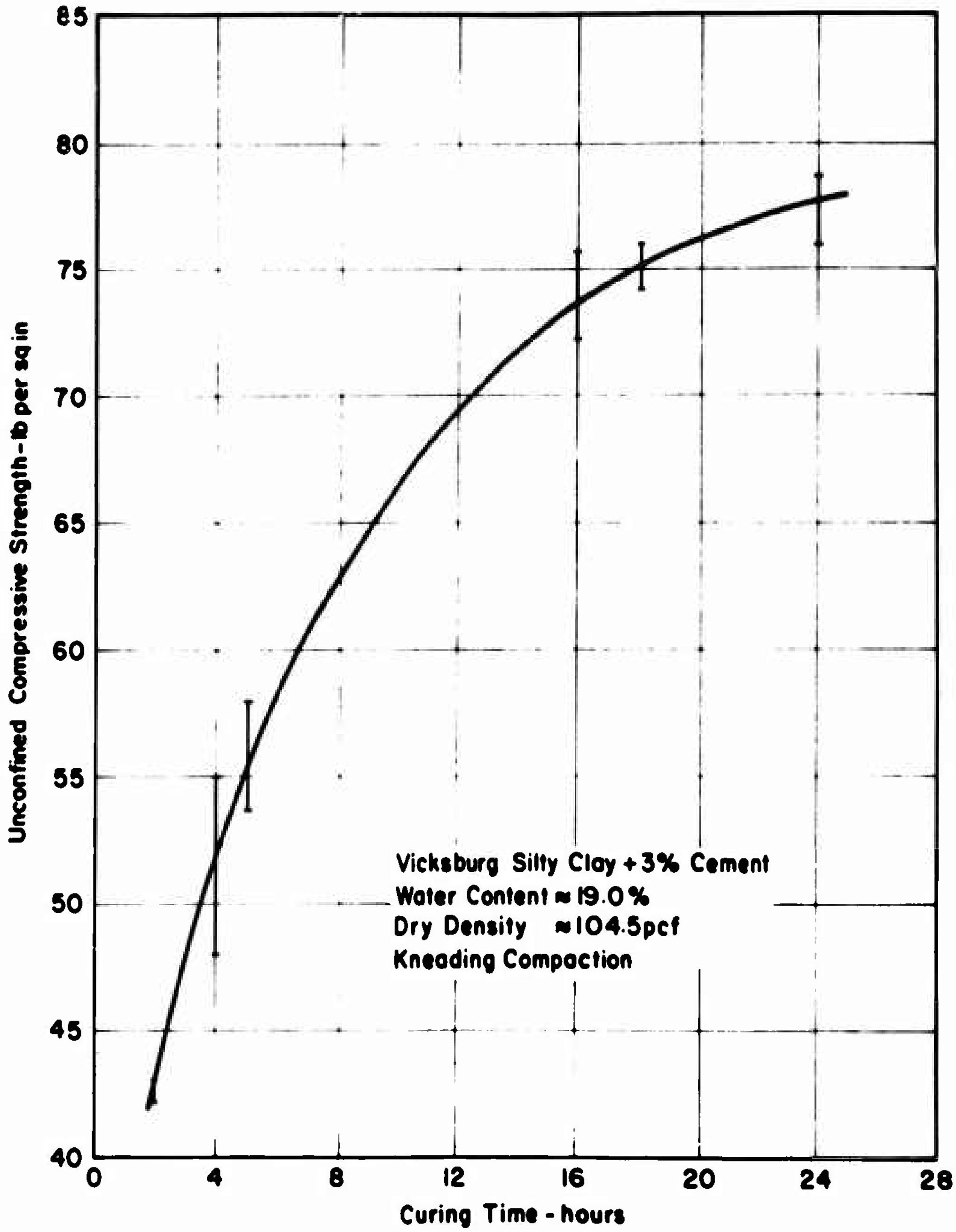


FIG.56 — UNCONFINED COMPRESSIVE STRENGTH AS A FUNCTION OF CURING TIME.

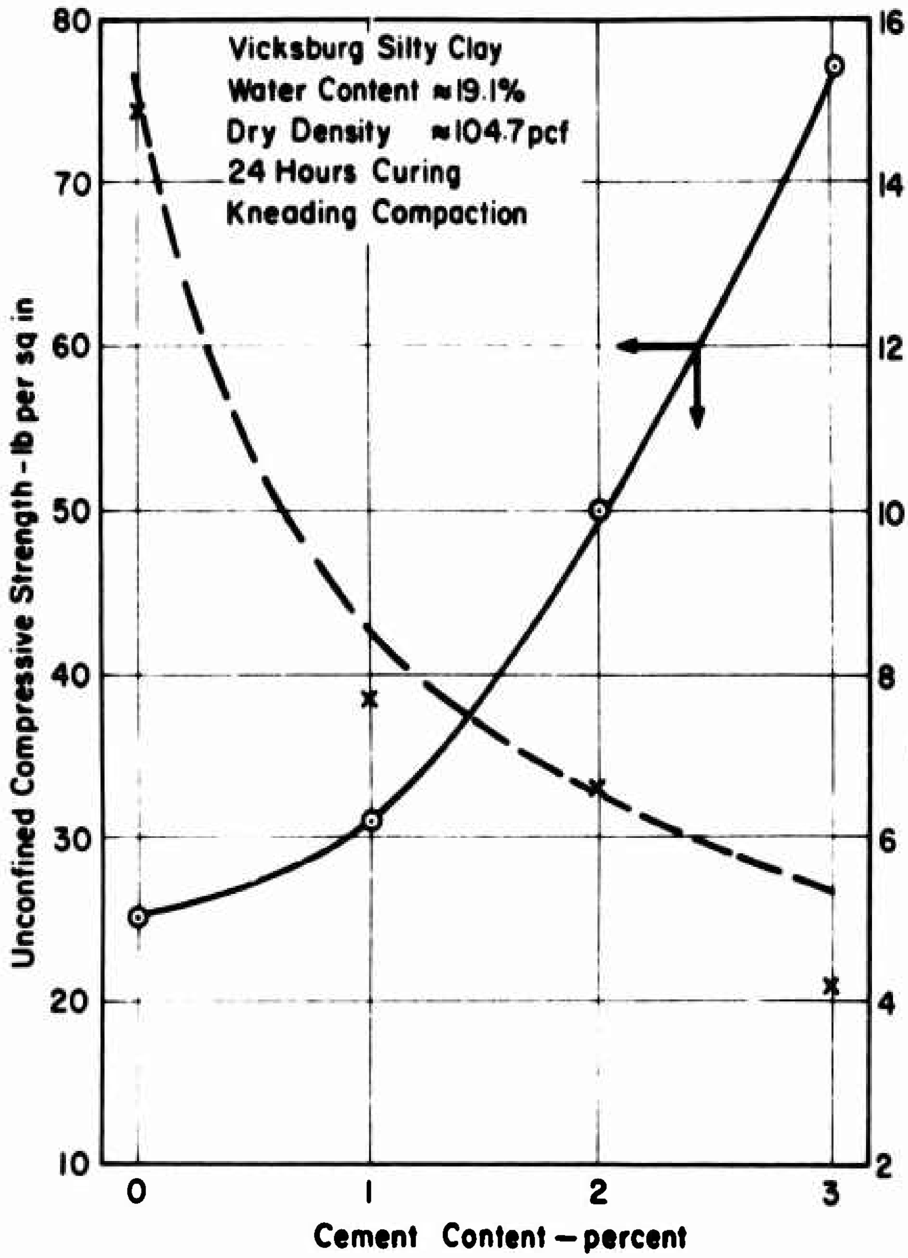


FIG.57— UNCONFINED COMPRESSIVE STRENGTH AS A FUNCTION OF CEMENT CONTENT.

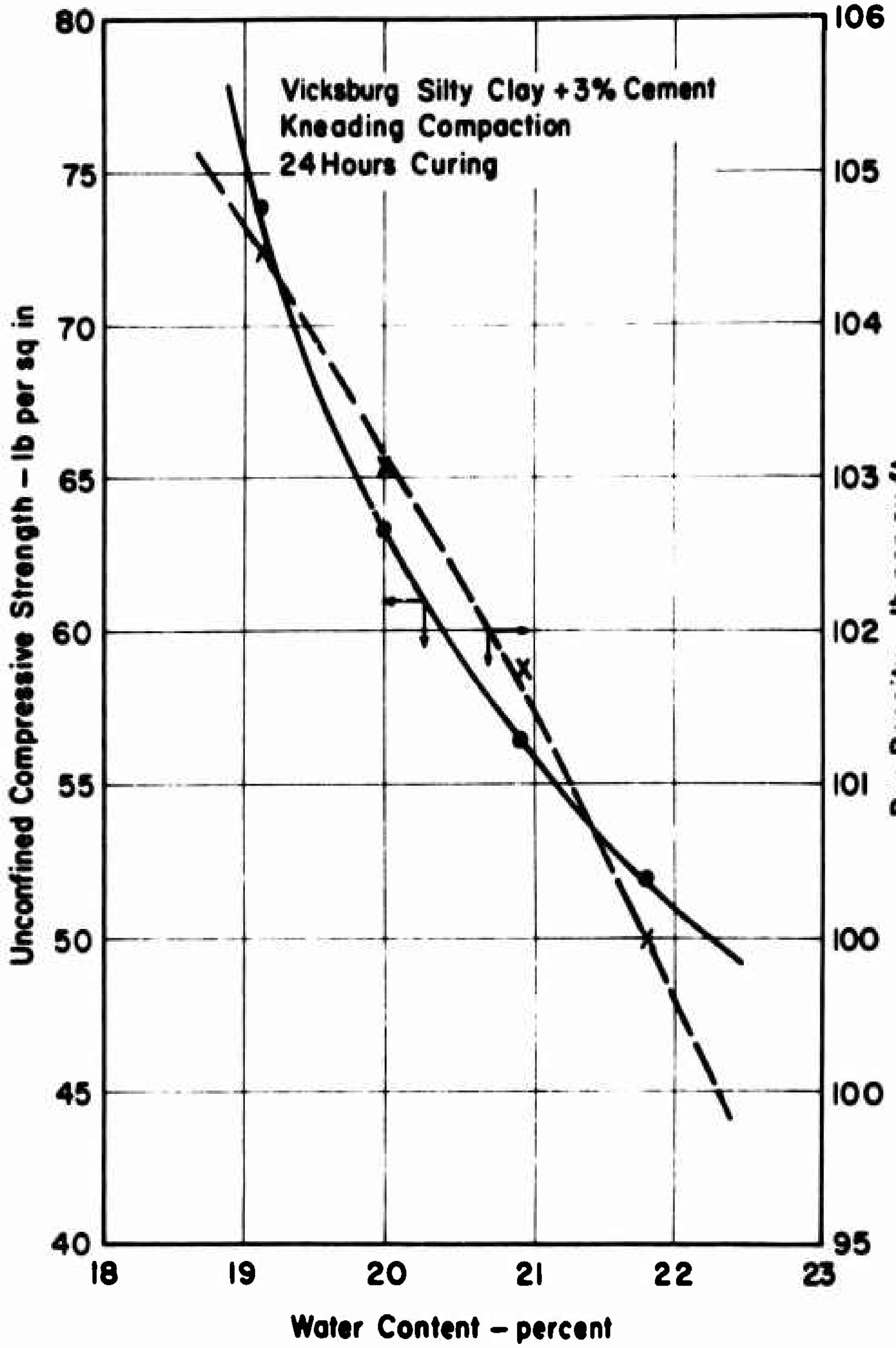


FIG.58– UNCONFINED COMPRESSIVE STRENGTH AS A FUNCTION OF WATER CONTENT.

TABLE 1 — EFFECT OF STABILIZATION VARIABLES ON PERFORMANCE

(1)	(2)	(3)	(4)	(5)	(6)	(7) = (5) ÷ (6)	(8)
Variable	Value of Variable	Unconf. Comp. Strength psi	Approx. CBR	Tensile Stress at Base of Stabilized Layer psi	Flexural Strength psi	Flexural Stress Level %	Comments
None*	Soil Batch 1**	73.7	20	13.6	18.9	72.0	Fatigue failure between 500 and 600 repetitions.
	Soil Batch 2***	77.7	20	13.6	21.8	62.5	Should satisfactorily carry more than 100,000 repetitions.
Cement Content	2%	49.6	14	10.5	11.5	91.3	Fatigue failure between 10 and 20 repetitions.
	2.5%	58.0	17	12.5	15.7	79.5	Fatigue failure at about 80 repetitions.
Curing Time	12 hrs.	69.3	20	13.6	18.7	72.8	Fatigue failure at about 400 repetitions.
	8 hrs.	63.2	20	13.6	16.5	82.5	Fatigue failure between 40 and 50 repetitions.
	4 Hrs.	52.0	15	11.0	12.0	91.5	Fatigue failure between 10 and 15 repetitions.
Water Content	21%	56.0	18	12.5	15.1	82.8	Fatigue failure between 40 and 50 repetitions.
	20%	63.0	20	13.6	16.7	81.5	Fatigue failure between 50 and 60 repetitions.
	19.5%	68.3	20	13.6	17.7	69.5	Fatigue failure between 1000 and 2000 repetitions.
Layer Thickness	20 in.	77.7	20	16.0	21.8	73.5	Fatigue failure between 300 and 400 repetitions
	18 in	77.7	20	19.0	21.8	90.5	Fatigue failure between 10 and 20 repetitions
	19 in.	77.7	20	17.3	21.8	79.5	Fatigue failure between 70 and 80 repetitions.

* Values are for initial water content = 19%, 3% cement, 24 hours curing, 22 in. stabilized layer, 18 000 lb. single-axle load, 70 psi tire pressure.

** These values pertain to analysis of water content effects.

*** These values pertain to analysis of cement content, curing time, and layer thickness effects.

5. The CBR and layer thickness values are used to obtain the tensile stress at the base of the stabilized layer from Fig. 53, thus giving the values for Column (5).
6. The flexural strength values in Column (6) are determined from Fig. 9, 10 or 55, whichever is applicable.
7. The flexural stress level indicated in Column (7) is obtained by dividing the values in Column (5) by those in Column (6).
8. The stress levels determined in this way are used in conjunction with the fatigue curve, Fig. 14, to estimate the number of repetitions to cause failure. if the allowable number of repetitions is less than 44 for the Class 1-R road or 1300 for the Class 2-R road then the pavement is considered inadequate. Fig. 19 was used to estimate fatigue characteristics at water contents other than 19 percent as indicated in item 3 under the listing of assumptions. The results of the comparison between the induced stress levels and the fatigue curves form the basis for the comments in Column (8).

According to the Corps criteria a Class 1-R road must satisfactorily withstand 44 repetitions of a 18,000 lb equivalent single axle load and a Class 2-R road must carry 1300 repetitions. The results in Table 1 show that a 22 inch pavement constructed with soil from batch 1 treated with 3 percent cement at a water content of 19 percent and cured for 24 hours should satisfy the criteria for the Class 1-R but not for the Class 2-R road. Similar construction using soil batch 2 should be adequate for both pavement classes. It may be seen that the cement content could be reduced to 2.5 percent and satisfactory performance for the Class 1-R road would still be expected. Curing times as short as 8 hours might be satisfactory for the Class 1-R road but more than 12 hours would be needed for the Class 2-R. The initial water content could be 19.5 percent for the Class 2-R road and up to 21 percent for the Class 1-R, all other factors being maintained at the basic design level. Finally for the Class 1-R road the thickness could be reduced to 19 inches without fatigue cracks developing.

The results of this type of analysis provide an indication of how the stabilization and construction variables may be expected to influence performance. Since in actual practice there will very likely be instances when treatment levels are below the minimum, abnormally high water contents may exist, construction to the full design thickness may not be practical, or some contigency will necessitate opening the construction to traffic prior to completion of the desired curing period, evaluations of this type may be of value in providing criteria for pavement use which will tend to prolong life and optimize performance.

Probably the greatest value of this analysis is that it provides a means for combining theoretical and experimental values in a manner which provides some justification for the extrapolation of experimental data to other conditions. It is planned to investigate further the validity of this approach in the coming months.

VII. SUMMARY AND CONCLUSIONS

This report is the second in a series presenting the results of studies of the behavior of stabilized soils under repeated loading. The long range objectives of these studies are the development of improved criteria for quality design of stabilized soils and establishment of suitable thickness design procedures for these materials for use in military roads and airfields. The Corps of Engineers (1963) soil stabilization requirements for military roads and airfields in the theater of operations provide the framework within which the studies have been organized.

The present report presents the results of experimental investigations and theoretical analyses in the following areas of interest in the overall problem:

1. A comparison of the behavior of cement-treated buckshot clay and cement-treated silty clay under repeated compressive stresses.
2. The behavior of cement-treated silty clay under the action of repeated flexural stresses.
3. The effects of repeated load frequency and duration.
4. Analysis of tensile stresses in pavements stabilized to satisfy Corps criteria and their relationship to fatigue failure and cracking under design loading conditions.
5. Analysis of the relationships between quality of stabilization and the wheel loads and pavement thicknesses at which treated silty clay will no longer satisfy Corps of Engineers criteria without pavement cracking.

The significant findings from these studies are as follows:

1. A comparison of the behavior of cement-treated silty clay and cement-treated buckshot clay under repeated compressive stresses showed that although soil strengths as measured by the CBR test prior to cement treatment and after a specified curing period are the same, the behavior under repeated loading may be distinctly different. Differences were also found under static load for specimens tested after different curing periods. For

both soil types the resilient modulus was found to be sensitive to stress intensity. The form of this variation was different in each case and appears to be related primarily to the cement content. Soil type affects significantly the influence of repeated loading on strength and brittleness.

2. The flexural strength and brittleness of cement-treated silty clay decrease with an increase in initial water content. Significant increases in flexural strength and decreases in strain at failure develop with increases in curing time. Resilient strain in flexure was found to be relatively insensitive to the number of load repetitions in the absence of fatigue failure. At any stress intensity the resilient strain amounted to about half the total strain. The resilient modulus in flexure was found to be more than twice that in compression; furthermore the sensitivity of resilient modulus to stress intensity was much less for flexural loading than compressive loading.

   The cement-treated silty clay can probably withstand repeated stress intensities of up to 60 percent of the flexural strength without suffering fatigue failure. Fig. 14 shows the relationship between stress intensity and member of stress repetitions to cause failure for stress intensities greater than 60 percent.

   The resilient modulus in flexure is sensitive to the water content at which the soil is stabilized. Increased curing periods lead to a marked increase in the resilient modulus in flexure. The increased brittleness associated with longer curing periods may lead to a greater probability of fatigue failure; insufficient data are available to evaluate this possibility.

   Repeated flexural stresses were found to cause an increase in static strength for those specimens that did not suffer fatigue failure. An attempt was made to find the cause for this apparently anomolous behavior, but the exact mechanism has not yet been clearly defined.

3. The most significant consequences of repeated load frequency appears related to the longer curing periods afforded the stabilized

soils in tests conducted at low frequencies. Total strains decrease and the influence of load repetitions diminishes with decrease frequency. Resilient strains decrease to much smaller values at large numbers of repetitions for low frequencies than at high frequencies. The variation of resilient modulus in compression with stress intensity at low frequencies was similar to that for the same soil with a higher cement content but tested at high frequency. This behavior is indicative of the increased stiffness that may result from increasing either the cement content or the curing period.

Repeated compressive stresses caused an increase in static strength with the magnitude of the increase being the greatest at the lowest frequency studied. Fatigue failure in compression is unlikely at stress intensities less than 100 percent of the initial static strength.

The resilient modulus in flexure was found to decrease with increasing repeated loading frequency. In addition the resilient modulus in flexure was found to vary with stress intensity at low frequencies. Thus the previous conclusions (from Fig. 13 and Report 1) that the resilient modulus in flexure is essentially independent of stress within the working range of stresses is not of general applicability.

4. Repeated compressive load durations had little effect on the total strain. Load duration had only minor effects on properties after repeated loading. In repeated flexure the permanent tensile strain was smaller and the resilient strain was greater at short durations (0.1 sec.) then at the longer durations (0.5 sec.). This may reflect the time dependency for development of permanent plastic strain. As a consequence of this behavior the resilient modulus may be less at very short load durations than at longer durations. In practice this effect may not be observed, however, because of the effects of mixed traffic and longer loading periods.

5. Analysis of the stresses induced in pavements stabilized to satisfy Corps of Engineers design criteria has shown that the flexural strength of the stabilized layer will be inadequate to prevent cracking. If cracking is to be prevented then pavement thicknesses substantially greater than indicated (Table 3, Report 1) for the various design loadings would be required. It does not follow however, that performance would be inadequate for forward area military operations, since in such situations, and for the short design lives specified, the formation of cracks and even the development of ruts may not impair the movement of vehicles.
6. A method for the analysis of the probability of fatigue crack formation for different strength, curing time, cement content and pavement thickness conditions has been suggested. An approach of this type, which combines experimentally measured properties under one set of conditions with theoretical analysis for the prediction of stresses and properties under another set of conditions is potentially useful for the study of the effects of stabilized soil quality variations on performance.
7. Many of the conclusions and predictions drawn from the studies thus far are in need of further investigation. It is hoped that the Corps experience record with respect to the performance of stabilized soil pavements constructed in accordance with the current criteria may be studied during the coming year. A test section is planned for purposes of studying repeated load behavior under more realistic field conditions, cracking phenomena, the usefulness of the laboratory repeated loading test for prediction of pavement behavior, and the applicability of layered system elastic theory to stabilized soil pavements.

REFERENCES

Bofinger, H. E. (1965) "The Fatigue Behavior of Soil-Cement," Australian Road Research, June 1965, pp. 12-20.

Corps of Engineers (1963) Soil Stabilization Requirements for Military Roads and Airfields in the Theater of Operations, Miscellaneous Paper No. 3-605, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Deacon, J. A. and C. L. Monismith (1966) "Laboratory Flexural-Fatigue Testing of Asphalt Concrete with Emphasis on Compound-Loading Tests," paper presented at annual meeting of Highway Research Board, Washington, D. C., January, 1966.

Mitchell, J. K., C. K. Shen and C. L. Monismith (1965) Behavior of Stabilized Soils Under Repeated Loading, Report 1, Background, Equipment, Preliminary Investigations, Repeated Compression and Flexure Tests on Cement-Treated Silty Clay, Contract Report No. 3-145 for U. S. Army Engineers Waterways Experiment Station, Vicksburg, Mississippi.

Seed, H. B., C. K. Chan and C. L. Monismith (1955) "Effects of Repeated Loading on the Strength and Deformation of Compacted Clay," Proceedings, Highway Research Board, Vol. 34, 1955, pp. 541-558.

Shen, C. K. and J. K. Mitchell (1966) "Behavior of Soil-Cement in Repeated Compression and Flexure," Highway Research Record No. 128, pp. 68-100.

Peattie, K. P. (1962) "A Fundamental Approach to the Design of Flexible Pavements," Conference Proceedings - Structural Design of Asphalt Pavements, University of Michigan, pp. 403-411.

TABLE A-1 – INFLUENCE OF CURING TIME ON THE UNCONFINED COMPRESSIVE STRENGTH OF VICKSBURG BUCKSHOT CLAY STABILIZED WITH 6 PERCENT CEMENT[a]

Sample No.	Molding Water Content %	Dry Density pcf	Curing Time	Compressive Strength - psi	Strain at Failure %	Water Content After Testing %	Tangent Modulus 10^2 psi
3	30.4	89.8	2 hrs.	44.5	2.81	30.2	31.5
4	30.4	89.8	2 hrs.	45.4	2.92	30.1	31.5
6	30.1	90.2	4 hrs.	59.4	2.58	29.8	52.5
5	30.1	90.4	4 hrs.	57.7	2.96	29.7	51.6
2	30.3	90.0	6 hrs.	63.6	2.99	30.0	48.0
1	30.3	90.1	6 hrs.	59.4	2.80	30.0	37.5
23	29.8	90.5	16 hrs.	75.4	3.24	29.4	39.0
22	30.0	90.3	16 hrs.	80.9	2.58	29.6	76.4
14	29.9	90.2	20 hrs.	84.3	2.35	29.7	101.0
16	30.0	90.2	20 hrs.	85.1	2.50	29.7	88.8
T-11	29.9	90.4	20 hrs.	85.1	2.52	29.6	91.3
T-12	29.9	90.4	20 hrs.	89.3	2.37	29.6	80.0
T-9	30.0	90.2	24 hrs.	83.9	2.20	29.8	85.0
T-10	30.0	90.3	24 hrs.	83.4	2.44	29.7	62.5
13	29.9	90.2	24 hrs.	86.3	2.23	29.6	71.5
15	30.0	89.9	24 hrs.	83.6	2.63	29.8	57.0
17	29.9	90.2	2 days	98.0	2.54	-	71.0
19	30.0	90.2	2 days	96.2	2.41	-	74.0
8	30.0	90.2	4 days	109.0	1.85	29.2	113.0
9	30.0	90.3	4 days	107.1	2.12	29.2	98.0
18	29.9	90.3	7 days	106.8	1.77	-	120.0
20	30.0	90.2	7 days	110.2	2.11	-	107.5
7	30.0	90.4	10 days	119.4	1.91	-	106.0
11	30.0	90.1	10 days	115.7	2.01	-	99.0
21	30.0	90.5	21 days	118.9	1.80	-	121.5
24	29.8	90.5	21 days	123.0	1.90	-	107.0

a. Dry Mix, Kneading Compaction.

TABLE A-2 — EFFECT OF REPEATED STRESS INTENSITY ON STRENGTH AND RESILIENCE OF CEMENT-TREATED BUCKSHOT CLAY[a] IN COMPRESSION[b]

Sample No.	Molding Water Content %	Dry Density pcf	Repeated Load Stress Level		Resilient Modulus at Varying Numbers of Load Applications, N. 10^3 psi			Strength After Repeated Loading psi	Strain at Failure %	No. of Load Repetitions	Tangent Modulus 10^3 psi
			psi	% of 24 hrs. Strength[c]	N = 100	N = 1000	N = 10,000				
37	30.1	90.2	10	11.6	91.0	100.0	167.0	97.3	2.19	24,000	10.0
32	30.2	90.0	10	11.6	91.0	91.0	100.0	93.3	1.92	24,000	15.2
39	30.1	90.3	20	23.3	26.1	27.4	44.4	100.9	1.82	24,000	22.2
31	30.2	90.2	20	23.3	26.5	25.6	36.4	97.0	1.94	24,000	29.4
33	30.1	90.3	30	34.9	19.2	19.5	33.0	102.8	2.00	24,000	32.3
34	30.1	90.2	40	46.5	24.7	25.3	40.0	101.4	1.76	24,000	50.0
35	30.2	90.2	50	58.1	18.2	20.0	31.4	99.8	1.57	24,000	66.7
40	30.1	90.2	55	64.0	20.1	22.0	36.7	102.4	1.07	24,000	28.6
36	30.2	90.3	60	69.8	13.9	12.9	18.0	110.0	1.27	24,000	19.6
30	30.2	90.2	70	81.4	19.7	17.2	22.6	112.4	0.96	24,000	24.4
38	30.1	90.2	75	87.2	12.8	10.7	-	-	-	4,922[d]	-
29	30.2	90.1	80	93.0	11.4	-	-	-	-	652[d]	-

a. Vicksburg Buckshot Clay plus 6 percent cement; 24 hrs. curing.
b. Load frequency, 20 repetitions per minute; load duration, 0.1 sec.
c. 24 hour strength = 86.0 psi.
d. Samples failed during repeated loading.

TABLE A-3 — INFLUENCE OF CURING TIME ON STRENGTH AND RESILIENCE OF CEMENT-TREATED SILTY CLAY[a] IN FLEXURE[b]

Sample No.	Curing Time days	Molding Water Content %	Dry Density pcf.	Repeated Load Stress Level		Resilient Modulus at Varying Numbers of Load Applications, N. 10^3 psi				Flexural Strength psi	Strain at Failure		Tangent Modulus 10^3 psi
				psi	% of Strength at Start of Test	N = 100	N = 1000	N = 5000	N = 10,000		10^{-2}[e] %	10^{-2}[f] %	
C-14	1	19.0	105.9	-	-	-	-	-	-	24.8[c]	8.9	-	27.8
15	1	18.9	106.1	12.5	60	72.1	74.7	78.4	82.6	28.7[d]	7.3	9.0	38.4
2	2	19.0	105.7	-	-	-	-	-	-	29.5[c]	7.8	-	33.6
1	2	19.0	106.1	14.2	60	93.0	93.9	97.4	100.1	30.7[d]	7.7	9.0	39.8
9	4	19.0	105.8	-	-	-	-	-	-	31.4[c]	8.0	-	35.2
17	4	19.0	106.2	15.8	60	-	-	-	-	32.7[d]	8.0	-	37.2
10	4	19.0	105.8	15.8	60	103.4	105.6	108.5	108.5	33.5[d]	8.0	8.8	41.0
22	4	19.0	105.7	15.8	60	91.0	93.7	95.4	96.0	-	8.7	12.0	38.0
7	6	18.9	106.0	-	-	-	-	-	-	32.8[c]	8.7	-	35.6
8	6	19.1	105.8	-	-	-	-	-	-	32.8[c]	8.1	-	36.6
5	6	19.1	106.0	16.8	60	126.2	128.2	132.8	135.4	34.7[d]	7.7	8.7	40.8

a. Vicksburg silty clay plus 3 percent cement.
b. Load frequency, 20 repetitions per minute; load duration, 0.1 sec.
c. Dummy strength.
d. Strength after 24,000 load applications.
e. Strain under static load only.
f. Static load strain plus permanent deformation due to repeated loading.

TABLE A-4 – EFFECT OF REPEATED STRESS INTENSITY ON STRENGTH AND RESILIENCE OF CEMENT-TREATED SILTY CLAY[a] IN FLEXURE[g]

Sample No.	Molding Water Content %	Dry Density pcf	Repeated Load Stress Level		Resilient Modulus at Varying Numbers of Load Applications, N. 10^3 psi			Flexural Strength After Repeated Loading psi	Strain at Failure		No. of Load Repetitions	Tangent Modulus 10^3 psi
			psi	% of 24 hrs. Strength	N = 100	N = 1000	N = 10,000		10^{-2}[d] %	10^{-2}[e] %		
B-44	19.0	105.0	-	-	-	-	-	18.7[b]	11.2	11.2	None	14.8
48	19.1	104.0	-	-	-	-	-	19.1[b]	11.1	11.1	None	16.0
6	19.0	105.2	0	0	-	-	-	20.4[c]	3.2[illegible]	3.2[illegible]	None	182.0
88	18.9	105.0	0	0	-	-	-	24.7[c]	7.7	7.7	None	34.8
59	19.0	104.7	0	0	-	-	-	20.6[c]	8.8	8.8	None	19.5
63	19.1	104.9	2.37	12.5	59.3	53.9	50.4	22.7	7.6	8.8	24,000	38.0
61	19.0	104.8	3.95	20.9	57.2	59.0	65.8	23.9	8.0	9.3	24,000	28.4
67	18.8	105.0	4.74	25.1	55.1	55.1	59.3	19.6	6.7	7.9	24,000	41.2
60	19.0	105.0	5.53	29.3	57.6	55.3	59.4	20.9	7.5	8.8	24,000	41.0
64	19.1	104.9	6.32	33.5	59.6	61.4	70.2	22.9	6.9	7.8	24,000	34.4
46	18.6	106.2	7.04	37.2	64.6	64.6	67.1	27.3	-	-	24,000	-
53	19.2	104.5	7.04	37.2	49.6	50.3	54.1	24.1	7.4	8.7	24,000	36.4
65	19.0	105.0	7.90	41.8	48.8	46.5	51.6	20.4	7.5	9.3	24,000	35.2
55	19.0	105.0	8.80	46.6	51.4	52.1	60.3	22.7	6.3	8.3	24,000	34.8
47	19.0	105.6	8.80	46.6	52.4	53.6	60.3	27.9	7.9	10.4	24,000	38.4
49	19.0	105.1	10.56	55.9	54.4	55.0	58.6	25.9	6.3	8.0	24,000	41.4
50	19.2	104.7	11.44	60.5	46.1	47.3	-	-	-	-	4,500[f]	-
56	19.0	105.0	11.44	60.5	57.2	52.9	57.2	25.7	7.6	15.1	24,000	35.6
80	19.1	105.1	11.85	62.7	47.8	47.0	52.0	-	-	-	310,855	-
92	19.0	105.1	12.20	64.3	49.4	49.8	56.0	-	-	-	200,535	-
66	18.8	105.1	12.20	64.3	50.2	51.7	58.1	23.5	6.9	8.5	24,000	34.4
57	19.0	105.0	12.32	65.2	48.5	49.3	57.3	26.5	8.0	10.2	24,000	31.4
68	19.8	105.2	12.64	66.9	50.1	49.4	54.9	-	-	-	24,000	-
74	19.2	104.7	12.64	66.9	40.5	40.5	-	-	-	-	6,931[f]	-
58	19.0	105.1	13.20	69.8	51.6	-	-	-	-	-	264[f]	-
52	19.2	104.7	13.20	69.8	34.6	-	-	-	-	-	137[f]	-
70	19.0	105.2	13.42	71.0	42.1	40.9	-	-	-	-	1,721[f]	-
54	19.0	104.8	14.08	74.4	-	-	-	-	-	-	54[f]	-
69	18.9	105.1	14.22	75.3	49.0	-	-	-	-	-	281[f]	-
71	19.0	104.9	15.80	83.6	50.0	-	-	-	-	-	160[f]	-
73	19.2	104.9	16.60	87.9	42.1	-	-	-	-	-	118[f]	-
72	19.2	105.0	17.40	92.0	-	-	-	-	-	-	11[f]	-
77	19.1	104.8	18.98	100.3	-	-	-	-	-	-	5[f]	-
5	19.2	104.6	15.68	83.0	-	-	-	-	-	-	40[f]	-
7	19.1	104.9	13.72	72.6	28.2	26.2	-	-	-	-	1,040[f]	-

a. Vicksburg silty clay plus 3 percent cement.
b. 24 hr strength samples.
c. Dummy strength (control) samples.
d. Strain under static load only.
e. Static load strain plus permanent deformation due to repeated loading.
f. Samples failed during repeated loading.
g. Load frequency, 20 repetitions per minute; load duration, 0.1 sec.

TABLE A-5 – INFLUENCE OF MOLDING WATER CONTENT ON STRENGTH AND RESILIENCE OF CEMENT-TREATED SILTY CLAY[a] IN FLEXURE[f]

Sample No	Molding Water Content %	Dry Density pcf	Repeated Load Stress Level		Resilient Modulus at Varying Numbers of Load Application, N, 10^3 psi			Flexural Strength After Repeated Loading psi	Strain at Failure[d] 10^{-2} %	No. of Load Repetitions	Tangent Modulus 10^3 psi
			psi	% of 24 hrs. Strength	N = 100	N = 1000	N = 10,000				
B 98	17.9	105.4	-	-	-	-	-	24.0[b]	8.2	None	26.8
99	17.9	105.8	-	-	-	-	-	22.8[b]	7.0	None	30.4
108	17.8	105.2	-	-	-	-	-	25.5[b]	6.5	None	40.6
17	17.7	104.9	0	0	-	-	-	29.3[c]	7.1	None	41.6
19	17.6	105.9	0	0	-	-	-	[illegible].1[c]	6.5	None	37.4
101	17.8	104.7	0	0	-	-	-	27.8[c]	9.0	None	30.6
102	17.6	105.3	11.8	48.9	90.0	84.3	89.4	27.3	5.3	24,000	58.2
103	17.7	104.6	13.8	57.3	78.0	76.7	78.9	29.2	5.6	24,000	48.0
20	18.3	105.8	14.4	59.7	62.6	62.6	67.0	32.8	6.1	24,000	55.0
106	18.0	105.3	15.8	65.4	92.1	89.6	92.8	30.4	6.7	24,000	44.0
21	18.2	105.3	16.2	67.2	66.7	63.8	64.3	33.5	5.3	24,000	63.0
107	18.0	105.3	17.7	73.4	83.0	80.5	84.4	33.3	6.5	24,000	54.0
112	17.8	105.3	19.5	80.9	75.8	-	-		-	388[e]	-
B-78	20.0	103.9	-	-	-	-	-	17.9[b]	13.3	None	16.6
84	20.2	103.7	-	-	-	-	-	14.7[b]	8.4	None	19.7
86	19.8	104.2	-	-	-	-	-	16.3[b]	9.4	None	24.5
91	19.8	104.0	-	-	-	-	-	17.9[b]	9.1	None	23.7
89	19.8	104.0	0	0	-	-	-	18.8[c]	10.0	None	23.9
104	20.0	103.9	0	0	-	-	-	18.3[c]	10.4	None	15.4
105	20.1	103.9	0	0	-	-	-	22.0[c]	9.3	None	22.7
93	20.0	103.7	7.9	47.3	47.2	48.9	52.1	21.9	6.7	24,000	43.2
110	19.8	104.3	7.9	47.3	54.6	57.8	66.0	24.9	8.5	24,000	38.6
111	19.8	104.1	9.2	55.1	58.1	59.6	64.1	24.7	7.6	24,000	34.2
B-82	20.1	103.9	10.4	62.3	-	-	-	-	-	35[e]	-
81	20.0	103.9	11.8	70.7	-	-	-	-	-	49[e]	-
87	19.9	104.3	13.2	79.1	34.7	-	-	-	-	241[e]	-
B-79	21.2	102.1	-	-	-	-	-	16.5[b]	9.1	None	16.6
96	20.7	102.7	-	-	-	-	-	13.1[b]	9.3	None	11.6
97	20.7	103.1	-	-	-	-	-	14.0[b]	7.5	None	16.6
109	20.7	103.2	-	-	-	-	-	17.9[b]	9.0	None	25.4
12	21.2	102.6	0	0	-	-	-	19.4[c]	5.0	None	83.5
113	20.9	102.9	0	0	-	-	-	20.1[c]	8.8	None	29.6
114	20.9	103.2	0	0	-	-	-	21.1[c]	11.8	None	16.4
115	20.8	103.2	7.2	46.7	55.4	57.6	64.2	25.0	8.1	24,000	32.0
120	20.7	103.3	8.4	54.6	56.0	56.3	59.6	-	-	24,000	-
116	20.8	103.1	8.4	54.6	50.9	52.9	60.8	20.9	6.9	24,000	46.0
131	20.9	102.7	9.6	62.4	37.2	39.0	46.2	23.4	8.1	24,000	32.8
132	20.9	102.6	10.8	70.1	51.2	50.0	56.9	20.8	7.5	24,000	31.6
118	20.7	103.6	10.8	70.1	45.6	44.6	55.9	24.4	7.4	24,000	32.4
136	21.0	102.6	10.8	70.1	55.7	56.6	-	-	-	4,290[e]	-
13	21.3	102.7	11.8	76.5	34.5	32.7	-	-	-	1,700[e]	-

a. Vicksburg Silty Clay plus 3 percent cement, 24 hrs. curing.
b. 24 hr. strength samples.
c. Dummy strength (control) samples.
d. Strain under static load only.
e. Samples failed during repeated loading.
f. Load frequency, 20 repetitions per minute; load duration, 0.1 sec.

TABLE A-6 — VARIATIONS OF MOISTURE CONTENT, DENSITY, AND STRENGTH WITHIN BEAM SPECIMENS OF CEMENT-TREATED SILTY CLAY[(a)]

Sample No.	Curing Conditions	Beam Sample - Before Trimming: Molding Water Content %	Beam Sample - Before Trimming: Dry Density pcf	Trimmed 3/4 in. Square Compression Samples From Beam: Final Water Content %	Trimmed 3/4 in. Square Compression Samples From Beam: Dry Density pcf	Compressive Strength psi	Strain at Failure %
B-133	1-1/2 hrs. curing	19.3					
Top[(b)]				18.6	103.5	36.1	2.86
Bottom[(b)]				18.3	105.8	47.0	3.87
B-140	1-1/2 hrs. curing	19.4	104.2				
Top				18.5	104.0	37.6	3.62
Bottom				18.4	107.1	37.9	3.19
B-134	24 hrs. curing	19.2	104.7				
Top				18.5	104.1	76.5	2.53
Bottom				18.3	104.9	72.5	2.46
B-142	24 hrs. curing	19.4	104.5				
Top				18.3	105.1	68.9	2.03
Bottom				18.4	104.3	61.4	1.92
B-135	After 70 percent repeated	19.1	104.8				
Top	loading - 24 hrs. cure			18.0	105.1	87.7	2.30
Bottom	24,000 repetitions			17.9	104.9	72.8	2.03
B-139	After 70 percent repeated	19.2	104.8				
Top	loading - 24 hrs. cure			17.8	102.1	91.6	2.35
Bottom	24,000 repetitions			18.0	104.0	91.6	2.43
B-141	After 70 percent repeated	19.4	104.7				
Top	loading - 24 hrs cure			18.4	104.2	69.3	1.70
Bottom	24,000 repetitions			18.2	103.6	72.7	2.24
B-147	After 70 percent repeated	19.1	104.9				
Top	loading - 24 hrs. cure			18.0	103.8	80.8	1.71
Bottom	24,000 repetitions			17.9	104.1	92.3	1.68
B-138	Dummy Strength	19.1	104.8				
Top				18.2	104.4	84.1	2.16
Bottom				18.2	104.1	86.5	1.89
B-143	Dummy Strength	18.9	104.7				
Top				17.9	104.6	95.1	2.66
Bottom				18.0	104.7	84.3	2.22
B-137	Dummy Strength	19.1	104.3				
Top				18.3	104.6	76.4	2.32
Bottom				18.1	103.6	83.3	3.06

a. Vicksburg silty clay plus 3 percent cement.
b. Denotes top and bottom of beam as compacted.

TABLE A-7 — INFLUENCE OF CURING CONDITIONS ON THE STRENGTH OF CEMENT-TREATED SILTY CLAY IN FLEXURE

Sample No.	Curing Conditions	Cement Content %	Molding Water Content %	Dry Density pcf	Sample Age When Tested days	Flexural Strength psi
D-1	Supported 46 hrs. 24 hrs. Moist. Rm. 22 hrs. in Const. Temp. Rm. (a)	None	19.0	106.9	1.9	9.1
D-2	Supported 24 hrs. Moist. Rm. Suspended 22 hrs. in Const. Temp. Rm.	None	19.0	106.7	1.9	8.3
C-14	Supported 24 hrs. Moist. Rm. Suspended 22 hrs. in Const. Temp. Rm.	3	19.0	105.9	1.8	24.8
C-16	Same as C-14 except inverted while suspended	3	18.9	106.1	1.8	24.8
A-20	Supported 29 days in Moist. Rm. Suspended 20 hrs. in Const. Temp. Rm.	3	18.8	106.0	30	33.9
A-22	Same as A-20	3	18.9	106.3	30	35.3
A-19	Supported 30 days in Moist. Rm.	3	19.0	105.7	30	37.1
A-21	Same as A-19	3	18.8	106.4	30	41.8

a. Support conditions:

Supported: 

Suspended: 

TABLE A-8 – EFFECT OF REPEATED LOAD FREQUENCY ON STRENGTH AND RESILIENCE OF CEMENT-TREATED SILTY CLAY[a] IN COMPRESSION[b]

Sample No.	Load[g] Frequency Rep. per min.	Molding Water Content %	Dry Density pcf	Repeated Load Stress Level		Resilient Modulus at Varying Numbers of Load Application, N. 10^3 psi				Compressive Strength psi	Strain at Failure Under Static Loads %	No. of Load Repetitions
				psi	% of 24 hrs. Strength	N = 100	N = 1000	N = 5000	N = 10,000			
F-35	10	19.5	104.4	-	-	-	-	-	-	69.8[c]	-	-
36		19.5	103.8	-	-	-	-	-	-	73.0[c]	-	-
37		19.3	104.3	-	-	-	-	-	-	73.6[c]	-	-
38		19.3	104.1	-	-	-	-	-	-	73.5[c]	-	-
41		19.0	105.0	-	-	-	-	-	-	78.4[c]	-	-
42		19.0	104.9	-	-	-	-	-	-	76.9[c]	-	-
14		19.2	104.7	-	-	-	-	-	-	100.4[d]	4.99	-
15		19.3	104.5	-	-	-	-	-	-	87.3[d]	3.91	-
16		19.3	104.5	-	-	-	-	-	-	89.0[d]	4.55	-
13		19.2	104.7	-	-	-	-	-	-	103.4[d]	3.96	-
6		18.9	105.1	-	-	-	-	-	-	97.4[d]	5.04	-
31		19.2	104.3	4.0	5.4	28.6	33.3	44.5	66.6	93.5[e]	3.53	24,000
22		19.1	104.0	8.0	10.9	9.1	10.7	16.7	25.0	96.3[e]	5.04	24,000
23		19.1	104.9	16.0	21.7	8.8	10.7	19.5	32.0	98.1[e]	3.58	24,000
30		19.2	104.4	24.0	32.6	5.2	5.4	6.7	8.3	99.6[e]	2.63	24,000
32		19.2	104.3	32.0	43.4	7.3	8.3	13.3	20.0	96.5[e]	2.26	24,000
33		19.2	104.6	40.0	54.2	9.1	9.8	14.0	17.8	100.9[e]	1.45	24,000
29		19.2	104.4	48.0	65.1	8.7	10.0	15.0	18.5	111.2[e]	1.01	24,000
20		19.1	104.4	56.0	76.7	10.8	11.9	17.5	22.8	128.1[e]	1.57	24,000
19		19.1	104.7	64.0	86.8	10.3	11.2	15.7	19.4	114.0[e]	1.03	24,000
18		19.1	104.6	72.0	97.6	9.6	10.6	14.6	16.4	151.3[e]	0.89	24,000
34		19.2	104.2	76.0	102.6	11.3	12.8	16.1	19.0	143.1[e]	0.86	24,000
17		19.1	104.8	80.0	108.4	10.7	-	-	-	-	-	195[f]
10	10	19.1	104.6	81.4	110.3	-	-	-	-	-	-	95[f]
2-3	2	19.1	104.7	-	-	-	-	-	-	86.6[d]	3.4	-
4		19.1	104.6	-	-	-	-	-	-	100.4[d]	4.5	-
10		19.2	104.2	-	-	-	-	-	-	96.6[d]	3.9	-
8		19.0	104.2	3.7	5.0	18.4	21.7	30.8	36.8	129.0[e]	4.4	24,000
7		19.0	104.5	7.4	10.0	23.0	33.5	41.0	61.5	127.2[e]	3.3	24,000
13		19.0	105.2	14.7	20.0	21.4	36.9	73.7	123.0	137.8[e]	2.8	24,000
14		19.0	105.3	22.1	30.0	8.9	13.2	22.1	31.6	135.6[e]	3.1	24,000
15		19.0	105.2	29.5	40.0	16.4	22.7	36.9	49.2	146.2[e]	2.1	24,000
12		19.0	105.1	40.0	54.3	10.1	16.2	30.3	42.6	152.2[e]	2.2	24,000
11		19.0	105.2	44.2	60.0	12.2	18.4	29.9	39.8	157.0[e]	1.7	24,000
9		19.0	104.5	51.6	70.0	11.4	16.1	28.7	43.0	155.2[e]	1.3	24,000
6		19.0	104.8	53.9	73.1	10.8	15.8	30.0	45.0	163.0[e]	1.4	24,000
5		19.0	104.9	66.3	90.0	11.7	14.9	25.5	38.5	157.6[e]	1.2	24,000
1		19.1	104.3	69.6	94.4	9.9	12.9	25.6	38.7	183.6[e]	1.1	24,000
2		19.1	104.2	81.1	110.0	11.6	-	-	-	-	-	348[f]
16	2	19.0	105.3	92.4	125.0	-	-	-	-	-	-	97[f]

a. Vicksburg silty clay plus 3 percent cement, 24 hrs. curing.
b. Load duration = 0.1 sec.
c. 24 hr. strength.
d. Dummy (control) strength.
e. Strength after repeated loading.
f. Sample failed during repeated loading.
g. Data for 10 repetitions per minute, given in Table 9, Report 1.

TABLE A-9 – EFFECT OF REPEATED LOAD FREQUENCY ON STRENGTH AND RESILIENCE OF CEMENT-TREATED SILTY CLAY[(a)] IN FLEXURE[(b)]

Sample No.	Load Frequency Repetitions per min.[(c)]	Molding Water Content %	Dry Density pcf	Repeated Load Stress Level		Resilient Modulus at Varying Numbers of Load Applications, N. 10^3 psi				Flexural Strength psi		No. of Load Applications to Failure	Strain at Failure 10^{-2} %	Tangent Modulus 10^3 psi
				psi	% of 24 hr. Strength	N = 100	N = 1000	N = 5000	N = 10,000	Dummy	After Repeated Load			
B-152	-	19.0	104.7	-	-	-	-		-	24.1	-	-	8.1	29.2
153	-	18.9	104.9	-	-	-	-	-	-	24.1	-	-	6.2	38.2
164	10	19.0	104.4	0.79	4.18	48.8	49.4	60.8	68.6	-	25.5	-	7.5	30.6
165		19.0	104.5	1.58	8.36	63.2	67.1	73.1	77.0	-	29.0	-	8.0	34.8
163		19.0	104.7	3.16	16.7	70.2	74.4	83.1	90.3	-	26.7	-	7.0	-
162		19.0	104.7	4.74	25.1	64.0	67.2	74.0	81.6	-	29.9	-	8.5	-
161		19.0	104.8	6.31	33.4	70.0	72.9	79.3	84.0	-	26.1	-	7.4	34.0
160		19.0	105.0	7.90	41.8	66.4	68.6	73.9	77.4	-	29.9	-	6.8	50.0
159		19.1	104.8	9.48	50.2	65.4	69.2	75.9	80.0	-	27.7	-	6.8	35.6
158		19.1	104.8	11.06	58.5	59.5	62.8	68.7	73.2	-	28.2	-	7.9	38.6
154		18.9	104.7	12.64	66.9	63.9	65.1	70.0	73.1	-	27.6	-	6.0	46.6
155		18.9	105.1	14.22	75.2	78.1	74.8	78.1	80.8	-	33.3	-	9.5	47.8
168		18.8	104.8	15.0	79.4	50.0	-	-	-	-	-	207	-	-
166		18.9	104.5	15.8	83.6	42.7	44.3	-	-	-	-	2233	-	-
167	10	18.9	104.8	16.6	87.8	-	-	-	-	-	-	114	-	-
B-175	-	19.0	104.3	-	-	-	-	-	-	25.7	-	-	9.5	24.4
179	-	19.0	104.7	-	-	-	-	-	-	28.1	-	-	6.8	40.0
183	2	19.0	104.7	3.16	16.7	59.6	68.6	85.4	95.8	-	38.3	-	8.8	42.0
181		19.1	104.7	4.74	25.1	60.7	65.9	79.0	90.3	-	42.5	-	11.8	54.0
180		19.1	104.7	7.90	41.8	58.5	71.1	89.8	101.2	-	40.9	-	9.4	44.0
178		19.1	104.6	11.84	62.7	53.9	55.4	65.5	73.6	-	42.6	-	8.2	53.2
169		19.3	104.6	13.4	71.1	67.0	72.8	81.2	86.4	-	-	-	-	-
174		19.0	104.7	15.8	83.6	45.1	47.6	-	-	-	-	2654	-	-
182		19.0	104.4	15.8	83.6	57.5	66.9	83.1	95.1	-	38.9	-	8.4	60.0
172	2	18.9	104.7	16.6	87.7	65.7	69.4	76.8	83.0	-	40.7	-	8.9	45.0

a. Vicksburg silty clay plus 3 percent cement; 24 hr. curing.
b. Load duration = 0.1 sec.
c. Data for 20 repetitions per minute given in Table A-4.

TABLE A-10 — EFFECT OF REPEATED LOAD DURATION ON STRENGTH AND RESILIENCE OF CEMENT-TREATED SILTY CLAY[a] IN COMPRESSION[b]

Sample No.	Load Duration[c] sec.	Molding Water Content %	Dry Density pcf.	Repeated Load Stress Level		Resilient Modulus at Varying Numbers of Load Applications, N. 10^3 psi			Strength After Repeated Loading psi	Strain at Failure Under Static Load %	Tangent Modulus 10^3 psi	No. of Load Applications
				psi	% of 24 hrs. Strength	N = 100	N = 1000	N = 10,000				
10	.2	18.8	105.3	22.1	28	9.0	9.8	17.7	85.4	3.59	9.4	24,000
9	.2	18.8	105.3	36.9	47	9.3	10.2	17.6	80.2	1.75	19.8	24,000
17	.2	19.0	104.7	44.2	57	7.7	8.5	13.2	87.0	1.45	11.7	24,000
26	.2	19.1	104.8	51.6	66	9.0	9.5	14.8	103.9	1.13	16.1	24,000
7	.2	18.8	104.8	58.9	76	8.7	9.5	14.0	111.8	0.75	17.0	24,000
16	.2	18.7	104.8	58.9	76	9.4	10.0	14.0	118.4	0.91	12.3	24,000
8	.2	18.8	104.8	66.4	85	9.9	10.8	15.8	122.0	1.04	16.2	24,000
18	.2	19.0	104.8	66.4	85	10.3	11.0	15.8	110.6	.94	11.0	24,000
25	.2	19.1	104.7	70.0	90	9.8	-	-	-	-	-	151[d]
51	.5	19.0	104.8	14.7	19	11.8	14.7	36.8	80.9	4.78	15.7	24,000
52	.5	19.0	105.0	29.5	38	7.6	9.1	16.4	73.4	3.52	18.9	24,000
33	.5	19.3	104.5	44.2	57	9.0	9.8	16.4	97.9	1.45	19.0	24,000
32	.5	19.4	104.5	58.9	76	9.2	10.5	15.5	110.0	.82	16.4	24,000
31	.5	19.4	104.7	66.4	85	10.8	11.6	16.8	115.8	1.05	13.7	24,000
50	.5	19.2	104.5	66.4	85	10.3	-	-	-	-	-	867[d]
49	.5	19.2	104.4	70.0	90	10.9	-	-	-	-	-	109[d]

a. Vicksburg silty clay plus 3 percent cement; 24 hrs. curing.
b. Load frequency = 20 repetitions per minute.
c. Data for 0.1 sec. duration given in Table 9, Report 1.
d. Samples failed during repeated loading.

TABLE A-11 — EFFECT OF REPEATED LOAD DURATION ON STRENGTH AND RESILIENCE OF CEMENT-TREATED SILTY CLAY[a] IN FLEXURE[b]

Sample No.	Load Duration[c] sec.	Molding Water Content %	Dry Density pcf.	Resilient Modulus of Varying Numbers of Load Applications, N. 10^3 psi				Flexural Strength After Repeated Loading[d] psi	Strain at Failure		Tangent Modulus 10^3 psi
				N = 100	N = 1000	N = 5000	N = 10,000		10^{-2}[e] %	10^{-2}[f] %	
E-1	0.5	19.1	104.8	62.8	66.1	70.6	73.1	18.2	6.8	8.5	29.5
2	0.5	19.1	104.8	66.6	65.8	67.9	70.5	17.3	7.8	9.5	26.0
3	0.2	18.9	105.0	71.0	79.4	83.5	87.5	21.2	-	-	-
4	0.2	19.2	104.7	67.1	69.0	71.6	72.7	18.2	7.3	8.9	24.0
5	0.2	19.0	104.7	60.6	61.4	65.6	70.5	21.8	8.4	10.5	28.5
8	0.1	19.4	104.4	54.5	53.4	57.5	60.2	25.5	8.7	10.3	32.4
9	0.1	19.4	104.4	60.5	60.0	60.9	63.8	21.0	8.3	10.0	30.8

a. Vicksburg silty clay plus 3 percent cement; 24 hrs. curing.
b. Load frequency = 20 repetitions per minute; repeated stress level = 60 percent.
c. Data for 0.1 sec. duration given in Table A-4.
d. 24,000 load applications.
e. Strain under static load only.
f. Static load strain plus permanent deformation due to repeated loading.

TABLE B-1

SOIL CLASSIFICATION DATA

	Vicksburg Silty Clay	Vicksburg Buckshot Clay
Liquid Limit, percent	35.1	58.8
Plastic Limit, percent	21.7	26.8
Plasticity Index, percent	13.4	32.0
Specific Gravity	2.65	2.70
AASHO Classification	A-6	A-7
Unified Classification	CL	CH

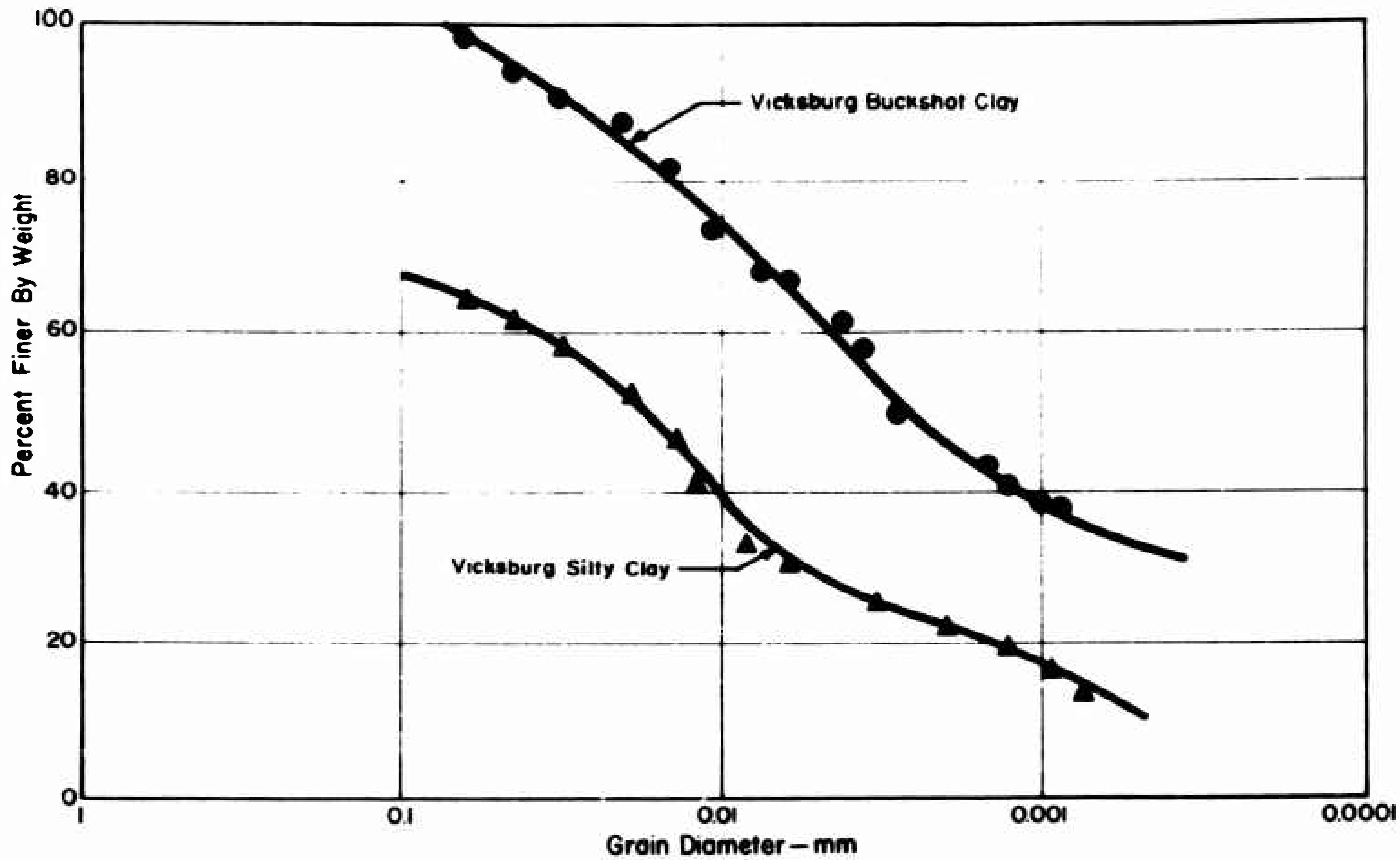


Figure B-1 - GRAIN SIZE DISTRIBUTION CURVES FOR SOILS USED IN STUDY.

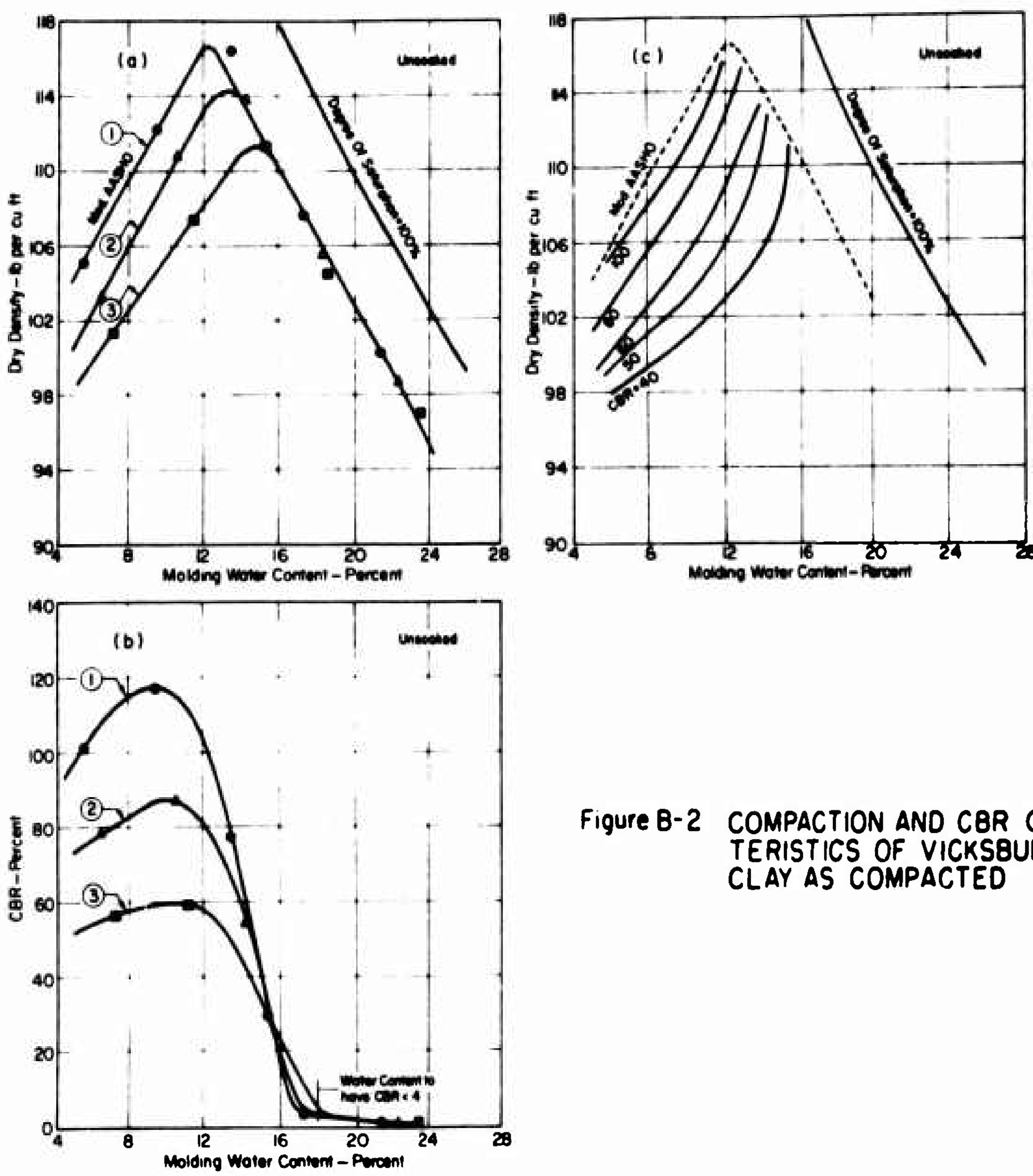


Figure B-2 COMPACTION AND CBR CHARACTERISTICS OF VICKSBURG SILTY CLAY AS COMPACTED

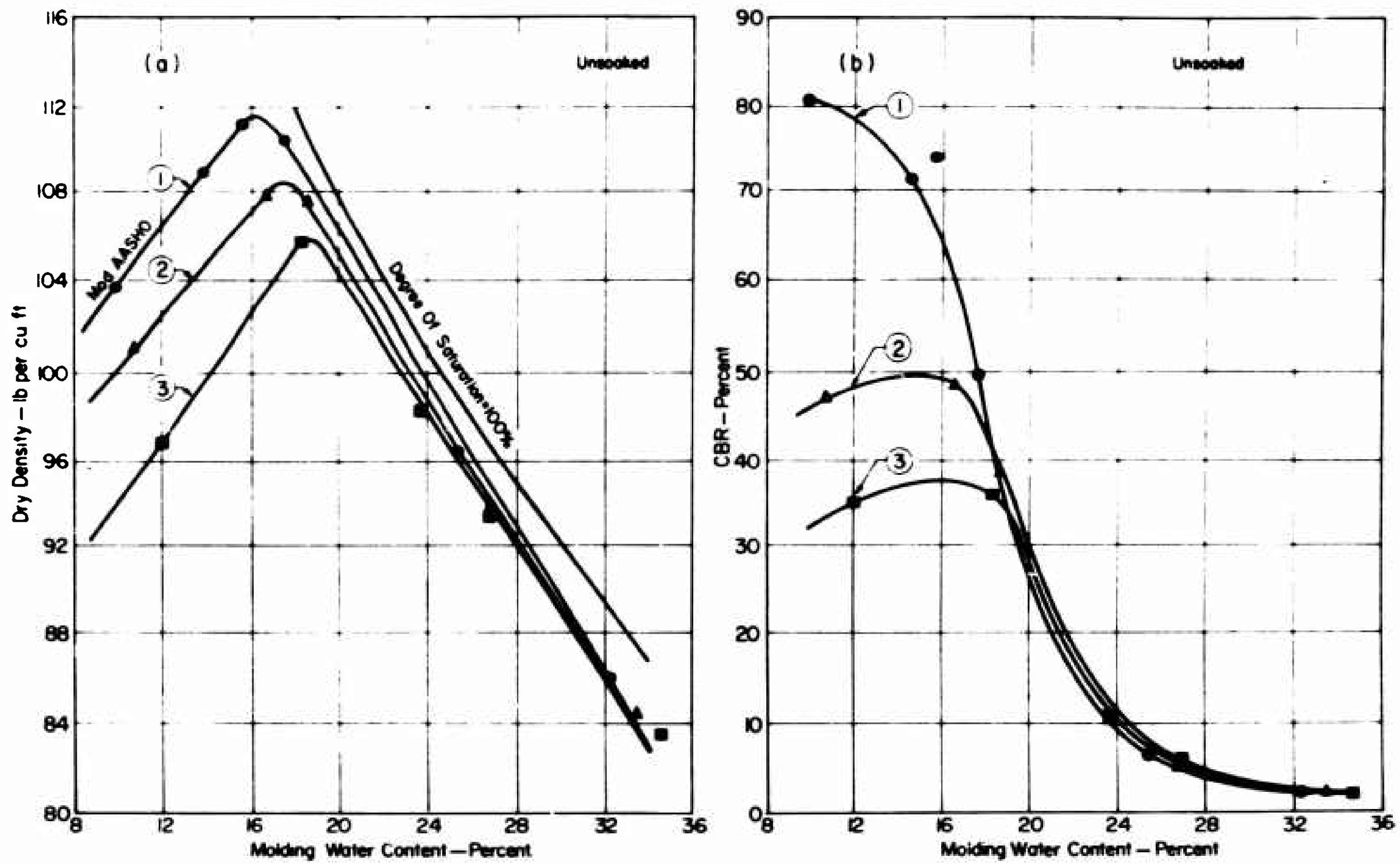


Figure B-3 - COMPACTION AND CBR CHARACTERISTICS OF BUCKSHOT CLAY AS COMPACTED.

Unclassified
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Department of Civil Engineering University of California Berkeley, California	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE
BEHAVIOR OF STABILIZED SOILS UNDER REPEATED LOADING; BEHAVIOR IN REPEATED FLEXURE, FREQUENCY AND DURATION EFFECTS, FATIGUE FAILURE ANALYSES

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Report 2 of series

5. AUTHOR(S) (First name, middle initial, last name)
James K. Mitchell
Carl L. Monismith

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
September 1966	12[illegible]	7

8a. CONTRACT OR GRANT NO. Contract No. DA-22-079-eng-414 b. PROJECT NO. 1-V-0-21701-A-04[illegible]-0[illegible] c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) U. S. Army Engineer Waterways Experiment Station, Contract Report No. 3-145

10. DISTRIBUTION STATEMENT

Distribution of this document is unlimited

11. SUPPLEMENTARY NOTES Conducted for U. S. Army Engineer Waterways Experiment Station, Corps of Engineers, Vicksburg, Miss.	12. SPONSORING MILITARY ACTIVITY U. S. Army Materiel Command Washington, D. C.

13. ABSTRACT

This report presents results of experimental investigations of the comparative behavior of cement-treated silty clay and cement-treated buckshot clay under repeated compressive stresses, the behavior of cement-treated silty clay in repeated flexure, and effects of repeated load duration and frequency in both compression and flexure. Analyses are presented relative to the adequacy of stabilized layers to withstand flexural stresses imposed by specified design trucks and aircraft. Fatigue probabilities are examined and a method for assessing the probable effects on performance of variations in stabilized soil quality is described.

DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

Unclassified
Security Classification

Unclassified
Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Cements						
Clay						
Soils--Loading						
Soils--Stabilization						
Soils--Stresses						

Unclassified
Security Classification